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Modelling and control of pitch-over phenomenon due to panic braking of motorcycles

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Modelling and Control of Pitch-Over Phenomenon due to Panic Braking of Motorcycles

By

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CERTIFICATE

This is to certify that the Master of Philosophy Dissertation titled "Modelling and Control of Pitch-Over Phenomenon due to Panic Braking of Motorcycles" is a bonafide record of the work carried out by Mr. Shijo Thomas in partial fulfilment of requirements for the award of Master of Philosophy Degree of Coventry University

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Abstract

Necessity of mobility of goods and people for economic development of a country has unleashed a boom in vehicle population in developing countries like India. Because of large economic disparity in the society, 2-wheelers on the road outnumber 4-wheelers almost 5:1. Using crowded roads, poor condition of roads and undisciplined traffic requires frequent starts and stops – some of them very abrupt. Pitching-over of 2-wheelers under such "panic braking" manoeuvre puts vast number of 2-wheeler riders under risk of sustaining severe injury as during pitch-over rider is thrown over the handle bar.

In the work presented here, key operational parameters responsible for pitch over of a motorcycle, and their relative influence on the phenomenon have been identified. "Pitch-over" envelope, to define unsafe zone, in terms of these parameters has been defined.

Mathematical models using analytical solutions were used to identify the key operational parameters influencing the pitch-over tendency of motorcycles. Relative effects of these parameters, like travel velocity, braking duration, brake bias, road gradient, and road friction coefficient, on threshold of pitch-over were studied using ADAMS model. This model was validated against available test results for some standard manoeuvres.

Duration of application of brakes, deceleration, was found to be the most important parameter for pitch-over. Motorcycle deceleration increases non-linearly with reduction in duration of braking. With adequate time, > 2 s in this case, tendency of pitch over is negligible. However, as available time reduces to 1 s or lower, a realistic scenario on a crowded street, motorcycle will have a tendency to pitch-over even at speeds lower than 40 km/h. This highlights the importance of developing a pitch-over control system for motorcycles operating in cities of developing countries.

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Acronyms

ABS – Antilock Braking System

ADAMS – Automated Dynamic Analysis of Mechanical Systems

ADB – Asian Development Bank

ASEAN – Association of Southeast Asian Nations

ASCII – American Standard Code for Information Interchange

CAD – Computer Aided Design

CG – Centre of Gravity

CRC – Constant Radius Cornering

ESC – Electronic Stability Control

ESP – Electronic Stability Program

HIV – Human Immunodeficiency Virus

INR – Indian Rupee

KSI – Killed and Serious Injury

LVDT – Linear Variable Differential Transformer

MBD – Multi Body Dynamics

NHTSA – National Highway Traffic Safety Administration

RPM – Revolution per Minute

TCS – Traction Control System

Chapter - 1: Introduction

In a developing country, compared to other mode of transportation, motorcycles are more widely used for commute. As the number of motorcycles is more in such countries accidents associated with motorcycle are also high in numbers. Pitch-over phenomena is quite frequently observed in motorcycle accidents. It occurs because of hard braking of front wheel or impact of front wheel with an obstacle. In this research work, the key parameters that are responsible for motorcycle pitch-over behaviour that occur during a panic braking scenario, the boundary conditions of pitch-over and possibilities of avoiding the same are discussed in detail. During pitch-over the rear wheel of the motorcycle lifts up from the ground and subsequently the rider is propelled over the handlebar. This scenario becomes much worse when a pillion rider also follows the trajectory of the rider in falling towards front of the motorcycle (Asian Development Bank 2001). In frontal impact or hard braking of front wheel, dynamic load transfer from the rear to the front wheel of a motorcycle causes the rear wheel to lift up, resulting in to pitch-over of motorcycle (Gillespie 2006). Extent of pitch-over (total angular displacement of a motorcycle from its horizontal position) determines the level of injury sustained by the rider. Hence, for adequate protection of the rider, a system that controls the extent of pitch-over is required for motorcycles. A mechanical or electronically controlled system that can alter dynamic load transfer pattern to maintain positive reaction on the rear wheels will help reduce the extent, or even completely prevent, pitch-over. To develop such systems, thorough understanding of the parameters involved and their interaction is very important. Very little research work has been conducted covering this aspect. This research work is aimed at this direction..

1.1. Proposed problem formulation Research Context

This research work is envisaged to develop, through better and detailed understanding of the pitch-over phenomenon. The title of the proposed research is **"Modelling and Control of Pitch-Over Phenomenon due to Panic Braking of Motorcycles"**. The proposed title is drafted to encompass proposed objectives.

1.2. Deliverable Research Aim and Objectives:

The aim of this work is to identify the safe operational envelope that helps to develop a control system for a motorcycle to reduce the occurrence of pitch-over event during panic braking

The system will specifically focus on maintaining stability even under rider response that is inappropriate for the panic situation. The specific research objectives are:

- To review literature on motorcycle dynamics and impact of operational parameters on tendency to pitch-over
- To develop a Multi-Body Dynamics model of motorcycle, simulate braking under various conditions
- To validate Multi-Body Dynamics models against test results
- To identify the parameters and their influence on causing pitch-over

1.3. Proposed Contribution to Knowledge

This research work brings out in depth understanding of motorcycle pitch-over phenomena and major parameters that contribute to pitch-over. It also gives a direction to find the solution for pitch-over. Most of the parameters that cause a motorcycle accident have a relation with velocity and braking efficiency.

1.4. Structure of the Thesis

Chapter 1: Introduction - (Introduction to motorcycle pitch-over, proposed problem formulation, overview of the thesis chapters)

Chapter 2: Review of pitch-over and pitch-over control techniques - (Critical review of the motorcycle dynamics, motorcycle braking, load transfer during braking and pitch-over. Modeling of motorcycle in multi-body dynamics software and finding factors leading to pitch-over through various simulations, various methods available to control pitch-over)

Chapter 3: Research methods and methodology - (Development of ADAMS model of motorcycle with specifications, details of motorcycle model, experimental test-set up)

Chapter 4: Results and discussion - (Discussion on the results with plots, graphs and tables, Conclusion and recommendation for future work)

Chapter - 2: Review of Literature

2.1 Introduction

Transport systems play a significant role in the economic and social development of any country. In general, developed road and rail networks are backbone of a country. In olden days, for long distance transportation of goods and people, rail network was suitable in India. However, large and well spread out network of improved roads has made road transportation the mode of choice for long distance transportation and travel, even in many geographical condition and terrains where development of railway infrastructure is a difficult task. This has increased the volume of traffic on roads. As the road vehicle population has increased, road accidents and resulting safety related issues have also proportionally increased. Hence, safety related design considerations for road vehicles have become very important in the design of vehicles (Asian Development Bank 2001).

In this chapter a critical review of dynamics and safety of road vehicles as a broad area has been presented. It reveals some of the major issues identified by vehicle manufacturers in this area. Vehicle dynamics has gone through four major stages of development, namely steering development, ride and handling improvements, subsystem development and interface of electro mechanical technology. From 1890 to 1920 several issues related to steering system such as mechanics of low-speed turning and over steer (stability) were identified and resolved. During the same time period ride and handling, mechanisms of front wheel shimmy issues were also handled by the technology developers (Gillespie 2006).

By 1950 there was a clear understanding of linear mathematical models of turning response such as, under steer, over steer, critical speed with over steer, natural frequencies of yaw and lateral acceleration response and influence of suspension properties. During 1970, technology advanced to the development of free-control stability and response mechanism. Modeling of non-linear response of vehicles up to their turning limits, influence of steering feedback on driver opinion and improved understanding of tires took place by this period (Gillespie 2006).

An initiative of Japanese automotive manufacturers in implementation of electro assisted mechanical system in vehicle during 1980's revolutionised automotive industry. Apart from the above, the influence of tyre properties on vehicle dynamics was also studied during this period.

Figure 2. 1 Four stages of revolution in vehicle dynamics (Gillespie 2006)

Figure 2.1 shows various stages of implementation of technology in vehicles for improvement in quality of vehicle dynamics. In recent years, second generation of such technologies such as ABS, TCS, ESC, steer by wire and brake by wire, have been implemented in vehicles. Firstly, most of these technologies are getting implemented in four wheelers, such as passenger cars. Subsequently, once this technology was proven in four wheelers it was adapted to two wheelers such as motorcycles and scooters. Considering vehicle dynamic aspects, both four wheelers and two wheelers have gone through many stages of development simultaneously. These advanced technologies, once successfully implemented in a four wheeler, were adapted into motorcycles also.

Vehicle dynamics became more important as the number of vehicles grew in densely populated countries with less experienced drivers. This has led to problems in countries like India. Increased number of vehicles being driven by drivers with poor skills has resulted in increased number of accidents and its associated fatalities. Hence, in countries like India vehicle dynamics related research and incorporation of safety feature in the vehicles is becoming very important.

2.2 Mobility in India

In the initial decades after independence, the railway network in India served as the backbone for long distance transportation of goods and people. In cities, with personal transport vehicles in short supply, people depended on public transport system.

With opening of economy in 1990s, easier availability of modes of personal transport resulted in steep increase in the number of vehicles on roads. This, coupled with streets being shared by people and multitude of vehicles of different types and sizes, has increased the number of accidents on roads. Along with accidents, fatalities associated with road accidents have also increased (Mavoori 2005). One reason for increased fatalities is also disproportionately large increase in the number of two wheelers. Affordability is probably one reason which has led to tremendous gain in market percentage by two wheelers over the past 50 years (Figure 2.2).

Figure 2. 2 Change in market share of two wheelers, cars, and buses in India (Singh 2007)

In India, about a decade back, 71% of total road vehicles were two-wheelers. Cars, jeeps and taxies contributed to about 13%, three wheelers about 4%, goods vehicles around 5%, buses around 1% and other facilities such as tractors, trailers and miscellaneous vehicle around 6% of total vehicle population in India (Figure 2.3).

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Figure 2. 3 Market share of various types of vehicles in India in 2005 (Mavoori 2005)

By 2011-12 the population of two wheelers increased to 78% of total vehicle population (Figure 2.4). Share of commercial vehicles, passenger vehicles, and three wheelers increased to 4%, 15% and 3% respectively (Society of Indian Automobile Manufacturers 2014).

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Figure 2. 4 Domestic Market Share of different vehicle types for 2011-12 (Society of Indian Automobile Manufacturers 2014).

2.3 Statistics of vehicle population and accidents in India

Two-wheelers, being more economic to purchase and maintain than four wheelers, have captured a substantial part of the market (Singh 2007). Since the number of two wheelers is large, accidents involving those require more attention. Hence, in India, means for accident reduction safety regulations have to be developed and implemented urgently. Extensive work is required to reduce accidents and severity of accidents involving two wheelers through improvement in their handling characteristics. To this end, it is required that vehicle manufactures and certifying bodies work together towards a safe driving environment. It is very important to improve the vehicle safety features through research and development in this field (Mavoori 2005).

2.4 Criticality of road traffic accidents

With increase in the number of accidents and related fatalities, human and economic toll of these accidents becomes one of the most critical problems for any country in terms of its social, health, economic, population and other developments. Globally, over the last few decades, contribution of road accidents to deaths has increased substantially. By 2020 it is expected to be the third largest killer "disease" – up from 9th place just a quarter of century back. (Table 2.1)

Table 2. 1 Change in rank of major causes of the Global Burden of Disease (Mavoori 2005)

In India in 1999, 80000 people were killed and 400000 people were injured in various road accidents (Asian Development Bank 2001). According to this study, traffic accidents are more dangerous killer than any deadly diseases (Mavoori 2005). Results of various road accidents related analyses and studies confirm the belief that vehicle accidents are on the rise in developing countries while the same are waning in the highly motorised developed regions. Motorcyclists and pedestrians are more prone to be in high-risk group throughout Asian countries, especially in India (Jacobs, Thomas, and Astrop 2000) because most of the time the driving conditions and driver behaviours are not good.

A study in 2005 found that in India more than 400,000 accidents were reported every year resulting in more than 60,000 fatalities (Mavoori 2005: 40). In general, the public health challenges due to these accidents are neglected even though they are the cause of such large number of serious and fatal injuries. These accidents have severe impact on social economy and health issues. Road accidents cause a huge liability on insurance sector as well as medical facilities in the country. Contribution of road accidents to fatalities in developed countries has increased to a higher degree than other reasons for fatalities. People injured or handicapped in these accidents add huge burden on medical facilities as well as already overworked health workers. This demonstrates how important it is to address the issues causing the road accidents and reduce the same (Mavoori 2005). Though the number of road accidents and its causes are different in different countries there are many common parameters contributing to an accident.

In most of the under-developed countries motorcyclists contribute significantly to these fatalities. Compared to other developing countries accident rate in India is very high. This is quite evident from comparison of road accident fatalities in India with the same in other ASEAN countries (Figure 2.5).

Figure 2. 5 Number of accidents in ASEAN region and in India from 1996 to 2003 (Mavoori 2005: 39)

In developed countries fatalities are 1 to 2 per 10,000 vehicles whereas the same in India is 14.54 per 10,000 vehicles (Mavoori 2005). In developing countries like Brazil, Mexico and Malaysia this rate is 4 to 6 per 10,000 vehicles. Country's overall loss of income due to these accidents is around INR 550 trillion which increases every year in direct proportion to the numbers of vehicle on the road (Mavoori 2005). Percentages of road accident deaths of road users of different types of vehicles in various countries are shown in Figure 2.6.

Figure 2. 6 Road users killed in various modes of transport as a proportion of all road traffic deaths in 1994 (Mavoori 2005: 20)

2.5 Severity of motorcycle accidents

Table 2.2 shows the contribution of motorcycle to overall road accidents of vehicles in Khon Kaen municipal area (Hurt, Ouellet and Thom 1981). When usage of motorcycle is more in an area chances of accidents involving motorcycle also increase proportionally.

Table 2. 2 Accident statistics of different vehicles involved in road accidents (Hurt, Ouellet and Thom 1981)

Table 2.3 shows comparison of motorcycle Mortality per 100 accidents (%) to other motor vehicles in China (Yang et al. 2008). From the comparison it is clear that motorcycle accidents are almost double that of other vehicles.

Table 2. 3 Mortality per 100 accidents (%) for motorcycles and other vehicles (Yang et al. 2008)

Other developing countries, like India, are also facing the same issue as motorcycle sales have drastically increased. In recent years, number of motorcycle increased multi folds. This has resulted in proportional increase in motorcycle accidents. Powerful motorcycles sold in these countries increase severity of accidents and number of causalities. Compared to earlier days trip lengths also have significantly increased by more than 50% (Clarke et al. 2007).

Among all modes of motor vehicle transport, motorcycles are most dangerous form of transport. A study (Hurt, Ouellet and Thom 1981) reveals that when number of motorcycle is 2% of total vehicle population it contributes to 10% of overall vehicle accidents. Rider not using a suitable helmet that protects vulnerable head can further increase severity of injuries. One of ADB studies conducted in Bangalore shows that the city has a serious road accident problem with 800 deaths and 14000 injuries every year. Two-wheeler riders and pedestrians contribute to most of these accidents (Asian Development Bank 2001).

Vehicle designers cannot dictate or control the conditions on the road to reduce the scourge of road fatalities. However, the designers can contribute to its reduction through designing in features that will reduce chances of accidents, and hence, road fatalities. To be able to do that understanding of various accident situations and understanding of Physics of these accidents is the necessary first step. In the next few sections, various types of accidents two-wheelers are involved in, and their causes are discussed.

2.6 Causes of motorcycle accidents

In a study to assess the risk perception of 2-wheeler riders, respondents were asked to choose “most risky” and “least risky” accident types from a list of six accident scenarios. Their responses are presented in Figure 2.7. Based on this survey conducted in the UK, various types of accidents and their contribution to the total number of motorcycle accidents were compiled. Loss of control due to improper riding technique, an event of high risk, is the cause of around 17.2% accidents. Even though collision with right turner is at a higher percentage, those accidents happen when rider is not following traffic rules.

Figure 2. 7 Risk perception of different types of 2-wheeler accidents (Clarke et al. 2004)

Figure 2.8 depicts the importance of rider action during a motorcycle accident. Not being able to correctly position the vehicles contributes to 16.7 % of accidents.

Figure 2. 8 Influence of various rider action during motorcycle accidents (Clarke et al. 2004)

Motorcycle accidents involving loss of control due to poor riding technique on curves and bends are common. Generally, most of the motorcycle accidents have very peculiar characteristics and when compared to other road accidents motorcycle accidents have very poor safety record. Physical condition of rider, misinterpretation of traffic and surroundings, other road users' perception of motorcycle etc., result in accidents, particularly at junctions. It is observed that generally older drivers with comparatively low driving experience and expertise are involved in these types of accidents (Cossalter et al. 2010). Most of the accidents are caused by loss of vehicle control and in particular failing to yield the right of way. Hence, motorcyclists are more prone to various types of accidents compared to other road users. Accidents resulting from loss of control on curves or bends are severe problems for motorcyclists (Ouellet and Vira Kasantikul 2006).

In the UK, measured by Killed and Serious Injury (KSI) rate per million vehicle kilometres, motorcycles are twice as dangerous as bi-cycles and sixteen times as dangerous when compared to cars. Motorcyclists, even though they constitute less than 1% of vehicle traffic, suffer more than 14% of total deaths and serious injuries (Cossalter et al. 2010).

2.7 Motorcycle accidents due to right of way violations

One of the most referred U. S. study (Jacobs, Thomas, and Astrop 2000) reveals that two main reasons for motorcycle accidents caused by other motor vehicles usually occur due to violations of right of way and rider running off the road on curves. Even in rural areas and in non-built-up roads, motorcycle accidents happen when riders are out for "drive for pleasure". During such pleasure drives the rider may not pay full attention on riding and it leads to loss of control, and ultimately accidents. The major reason for the difference in motorcycle accidents from other types of vehicular accidents is that initially car or truck drivers will concentrate on the same class of vehicle as theirs, paying low importance to two-wheelers. As a result in most cases involving right of way violation, it is the larger vehicle which violates motorcycle rider's right of way (Cossalter et al. 2010) and causes accident.

In some cases, accidents happen in built-up roads due to ignorance of the driver of the other vehicle, who is taking a turn or a U-turn in front of a motorcycle rider. Similar accidents due to ignorance of pedestrians crossing roads or a vehicle driver looking back but not seeing the motorcycle rider, concentrating on an obstacle that seems to be of critical importance in their experience, are also reported. In certain cases, under-estimation of speed of the approaching vehicle and decision to proceed ahead is also a potential hazard. Due to inattention blindness, where an object falls outside the centre of the visual fields of a rider, can also cause an accident (Cossalter et al. 2010). Motorcycle riding also involves more complex simultaneous actions like, physical co-ordination between balancing of vehicle, counter-steering, application of front and rear brakes, throttle opening in curves etc. Division of attention in these activities adds to risk of accidents.

2.8 Motorcycle accidents due to rider response

In most cases of motorcycle accidents, driver response can have a major negative impact on accident. For reduction in the number of two-wheeler accidents and improvement in the safety of the riders, a number of control systems have been developed and implemented in two-wheelers. In few tests it has been observed that there is no significant difference in driver response with active or passive safety systems. For example, if driver response is aimed at avoiding a crash, the drivers of vehicles with ABS have a tendency to combine braking and steering consecutively prior to a collision more often than the drivers of vehicles without ABS. The improper driving response on roads can happen due to:

- Excessive speed
- Unawareness of use of advanced active systems equipped in vehicle
- Overconfidence on active safety equipments with wrong understanding of its operational sequences

2.9 Motorcycle accidents due to unsafe riding behaviour

Improvements in roadway designs and development of vehicle safety devices based on those existing surrogate safety measures can increase transportation safety. However, simultaneously changes in driver behavior should be met since increase in frequency of unsafe driving behavior may lead to increase in number of motor vehicle accidents. Methods used for examination of driver behaviour in controlled environments for familiar psychological research were also found to be ineffective (Cossalter et al. 2010). Area of defensive riding skills can improve by introducing efficient measures to change the attitude of a rider towards the risk involved in motorcycle riding (Cossalter et al. 2010).

2.9.1 Factors influencing riding behaviour

Major factors that influence driving behaviour of riders include riding environment, road design, weather, illumination, road conditions, obstacles, vehicle speed, headway, traffic flow and time-to-collision. Apart from these, vehicle characteristics and personal factors like physiological data also play a major role. Even though these factors influence riders' driving behavior, in this work their impact has not been taken into consideration. Use and misuse of safety systems by drivers can happen because of human errors and violations of driving rules. Drivers' knowledge of safety systems should include theoretical knowledge as well as practical knowledge (training and experience). Statistically, accident proneness of motorcycles is influenced by most of the behavioral and all of the non-behavioral factors.

2.9.2 Child riders

Children as motorcycle riders are exposed to higher risks of injury and associated disabilities. These children behaviorally assume the roles of an adult and try to copy adult attitudes of risk taking during a crash event (Cossalter, Lot and Maggio 2004).

2.9.3 Inebriated riders

Many fatal accidents involving motorcycle were caused by alcohol affecting riders' ability to perform collision avoidance action correctly and in time.

2.10 Effect of training on motorcycle riding

Large number of untrained and poorly trained riders considerably increases the probability of accidents involving two wheelers. A thorough training on motorcycle riding technique enables a rider to use motorcycle efficiently with minimum accidents. However, studies reveal that rider training resulted in significant reduction in motorcycle accidents in early 1980s and mid 1990s. But in recent years, the trend appears to be reversing. No significant advantage of rider training was observed and in most cases very basic human factors caused the accident. Study reveals that a large percentage (68.9%) of riders did not take any collision avoidance action at all during a crash. While detection failure is considered in most cases other vehicle driver did not see or were too late to see the motorcycle (Ouellet and Vira Kasantikul 2006).

Even highly skilled bicyclists, moving at a much slower speed than a motorcycle, can just about manage to avoid a crash through proper manoeuver (Sharp 2001a). In many accidents, the ability of rider to counter steer and swerve was essentially absent. Also, it is observed that rider training had negligible, if any, improvement in their collision avoidance performance. Most of the riders in motorcycle accidents showed very poor avoidance skills. About 30% of riders did not take any stability control action during a crash situation (Ouellet and Vira Kasantikul 2006). Most of the riders who attempted to take an evasive action either chose a wrong action or poorly executed their selected evasive action.

Vehicle manoeuvring and handling response of an untrained rider and a trained rider during a panic situation was more or less same and inappropriate. During panic braking and manoeuvring most of the riders took wrong collision avoidance action and few executed their action poorly. One study in Thailand shows that 50% of riders took no evasive action to avoid a collision. Around 64% of people took wrong evasive action and around 60% failed to execute the action they chose. Compared to the US riders, it was also found that the Thai riders are better in controlling motorcycle braking and avoiding rear wheel skidding (Ouellet and Vira Kasantikul 2006).

Table 2. 4 Collision avoidance actions by riders with different levels of training (Ouellet and Vira Kasantikul 2006: 5)

Percentage of people applying only front brake under a panic situation was higher in developing countries where training facilities and knowledge transfer on riding a two-wheeler is comparatively low. Table 2.4 shows the effect of rider training on usage of various collision avoiding actions (Ouellet and Vira Kasantikul 2006). This study suggests that extensive research is needed in the area of collision avoidance performance either by the rider or by an intelligent system fitted in motorcycle. One more factor contributing to this result was the power of motorcycle used in Thailand and the US. Comparatively lower power vehicles used in Thailand are slightly easier to bring under control (Ouellet and Vira Kasantikul 2006).

Figure 2. 9 Cumulative distribution of time from start of event to impact (Ouellet and Vira Kasantikul 2006: 4)

While performing collision avoidance action the time available to perform the same is very important. In most cases it is found that time available for a collision avoidance action is too short. Figure 2.9 shows total time taken to impact from precipitation of the motorcycle during an accident. It is observed that in the US median value is 1.9 s whereas in Thailand it is 1.7 s. Almost 20% of the riders had more than three seconds for collision avoidance action whereas others had less than three seconds for their evasive action. In a collision avoidance study conducted in Thailand, 48.8% of riders did not take any action before impending collision. Only 11.2% of riders took correct action of simultaneous rake and swerve (Ouellet and Vira Kasantikul 2006). Effectiveness of training riders in proper body movements to prevent pitch-over is also very limited, mainly because it calls for recalling and executing the manoeuvres in a very short time frame.

Table 2.5 shows how often different collision avoidance actions are taken by riders in Thailand. No significant differences were found when similar studies were conducted in the US. Some riders trained in collision avoidance by police department were made to face a collision scenario. Their responses in taking evasive action were very similar to those of normal untrained riders.

Table 2. 5 Frequency of various collision avoidance action in Thailand (Ouellet and Vira Kasantikul 2006: 5)

Table 2.6 shows the comparison on effect of training on various collisions avoidance scenarios (Ouellet and Vira Kasantikul 2006).

Table 2. 6 Effect of training on Collision avoidance (Hurt, Ouellet and Thom 1981)

2.11 Accident reconstruction to identify rider behaviour

It is difficult to study the causes of any motorcycle accident in real time. However, for post-accident condition, use of road accidents investigation methodology is used for finding reasons for the accident. In general as a common measure, researchers use deformation of front suspension of motorcycle for evaluation of impact speed (Clarke et al. 2007). However, these studies consider only perpendicular impact of a moving motorcycle to a stationary automobile. In a real accident scenario relative speed of the two vehicles, vector component of the velocity, impact force, vehicle braking performance and if any modification to the vehicle done etc. have to be considered. In depth investigation of collision avoidance skill of a motorcycle rider is reported in various studies and in most of the cases, it was difficult to construct the pre-crash events (Clarke et al. 2007).

Collision avoidance performance of motorcycle riders are assessed by sequential determination of pre-crash actions. Arranging pre-crash events in chronological order is very important to be able to understand the crash avoidance actions of the rider. At the same time, this task is very difficult because of high number of events taking place over a very short duration of time. Event factors such as speeds, acceleration, distances and directions are determined in every case with available time for crash once the initiation of the precipitating event occurs and terminate it with the impact of crash.

2.12 Motorcycle accidents due to improper braking

Motorcycle-related vehicle safety research at NHTSA focuses on effective braking system development (Clarke et al. 2007). It is found that lack of knowledge of brake application leads to an accident. For example, by applying only the rear brake, rider allows the motorcycle to skid. Some forget to counter steer and swerve to avoid accidents. Few others apply brake hard, leading to skidding of rear wheel. Some riders under brake front wheel causing reduction in deceleration and increase in stopping distance (Hurt, Ouellet and Thom 1981). One of the other issues faced by riders is over braking of motorcycle under panic situation. During a panic braking scenario while velocity is reduced to 50% of its initial velocity, motorcycle might have crossed 75% of its available stopping distance. In this scenario if rider feels that the motorcycle is not going to stop on remaining 25% of distance then he applies the brake harder and that leads to wheel lockup, which leads to loss of control and possible crash or collision (Hurt, Ouellet and Thom 1981).

A study reveals that when motorcycle is moving at a very slow speed, rear dominated hard braking will lead to skidding of rear wheel and eventually cause loss of total control of the vehicle. In another scenario if motorcycle encounters a front dominated hard braking then load gets transferred to the front wheel and it leads to pitch-over of motorcycle (Cossalter, Lot and Maggio 2004).

Single point control for application of front and rear brake may be a solution in collision avoidance conditions. Though most of the riders prefer to have individual front and rear brake control system a single point control reduces rider effort for balancing brake pressures. The study highlights how lack of skill for collision avoidance of a rider leads to accidents (Hurt, Ouellet and Thom 1981).

2.13 Two-Wheeler Pitch-Over

Two wheeler riders can use different manoeuvres to avoid serious accidents. However, these manoeuvres of riders in a panic situation greatly affect the dynamics, and hence, the stability, of a motorcycle. In case of a motorcycle the rider has to control a strong dynamic coupling between rigid bodies like frame and wheels and flexible connecting parts like fork and suspensions. During manoeuvring and panic braking, it becomes a very difficult task for a rider. The dynamic behaviour of a motorcycle is heavily dependent on the interaction between the tyre and the road. Tyres provide contact between wheel and road surface and help transfer inertial, braking and friction forces to enhance the ability to steer under acceleration or braking. Overall vehicle dynamics is greatly affected by riders' behaviour (Mavoori 2005). In some accidents, rider applies only front brake very hard. In such cases front wheel locks up and this lead to lifting of rear wheel (Hurt, Ouellet and Thom 1981). This response of the motorcycle is known as pitch-over of motorcycle and it is shown in Figure 2.10, generated from an ADAMS simulation.

During hard braking of front wheel, the front wheel gets locked up and the rear wheel weight is transferred to the front wheel. The moment about the centre of gravity of motorcycle causes it to pitch forward. Two major criteria for pitch-over; the loss of normal force at the rear wheel due to the load transfer towards front, and the sharp deceleration, greater than 1g, of the vehicle. The process of pitch-over follows the following pattern,

- Hard braking of front wheel with deceleration above 1g
- Locking up of front wheel
- Generation of additional moment of dynamic force about vehicle CG.
- Rotation of the vehicle because of this moment
- Decrease in rear wheel reaction force due to transfer of dynamic load to the front wheel
- Lifting up of the rear wheel from the ground leading to pitch-over

Figure 2. 10 Motorcycle Pitch-over

A study reveals that during panic braking, to avoid a collision, about 0.8% of people apply only the front brake. Motorcycle pitch-over can also be caused by impact to the front wheel and occasionally by hard brake application of the front brake. In extreme conditions, the rider of the motorcycle can be propelled over the handlebars as the motorcycle pitches over.

2.13.1 Effect of location of centre of gravity in Pitch-Over

In the area of vehicle stability, a two wheeler faces issues like pitching, rolling and yawing during braking or going around a curve. Location of centre of gravity of vehicles plays a vital role in controlling the pitch, roll and yaw behavior of a vehicle. In case of a four wheeler, compared to a two wheeler, the centre of gravity location is much closer to the ground level. Because of the high location of centre of gravity, a two wheeler has greater tendency of pitch-over than a four wheeler. This pitch-over tendency results in higher number of accidents in two wheelers. Some of the parameters that exacerbate pitch-over behavior in two wheelers are discussed in the following sections.

Height of the centre of gravity of a motorcycle increases with a rider and that will increase the tendency of the motorcycle to pitch over. While riding uphill, pitch-over may not happen even due to a hard frontal braking but on a downhill, chances of pitch-over increase. With proper modulation of brakes and rider counteractions, pitch over can be reduced in normal riding. By adjusting the CG location with driver actions, like, the movement of rider weight back and down, it is possible to achieve larger decelerations and reduced pitch-over effect. During panic braking a low centre of gravity and large mass of the motorcycle body will reduce tendency of the motorcycle to pitch-over (Sharp 2001b).

2.13.2 Effect of Rider Posture in Pitch-Over

Two wheeler dynamics and its stability are directly dependent on the driver behavior and posture during braking and acceleration (Sharp and Limebeer 2004b). Wrong posture and actions can increase the probability of pitch over during braking (Limbeer, Sharp and Evangelou 2001b). Not leaning towards front during high speed manoeuvring, thighs spread out during manoeuvring, not holding handlebar grips properly etc. are some of the wrong postures and actions that enhance possibility of pitch-over. Leaning of the rider upper body changes the rider centre of gravity location, which also can contributes significantly to pitch-over. A study also reveals that muscular power of rider and posture may be highly influential for the desired motions during the control action of motorcycle (Jacobs, Thomas, and Astrop 2000).

2.13.3 Deceleration

Time available for a rider to plan, decide and execute a collision avoidance action is very small. In general between sensing an impending collision and the actual event, a motorcycle rider gets less than 2 seconds to complete all collision avoidance action (Kneebone 1992). Hence, deceleration of motorcycle is very critical during brake application. Appropriate deceleration rate must be achieved within the available time. Theoretical maximum deceleration rate of a conventional motorcycle is restricted to about 0.6 g on level roadway (Pein 2004). If deceleration is maintained within the allowed range then there will not be any total load transfer towards front wheel. As a result the rear wheel will never experience a zero force on it and this type of braking will never cause a pitch-over. It is found that only a highly skilled motorcyclist using his best possible skills may be able to maintain this 0.6 g deceleration. Majority of riders will be able to achieve the deceleration far lower at about 0.35 g (Sharp 2001a).

2.13.4 Mechanical Trail

Mechanical trail is a design parameter and is described as the vertical distance between the steering axis and the contact point between front wheel and the ground (Figure 2.9). Higher mechanical trail, by lowering the centre of gravity, makes a motorcycle more stable and easier to ride. But when mechanical trail is low a skilled and alert rider may have better path control (Hurt, Ouellet and Thom 1981).

Figure 2. 11 Trail of a typical motorcycle (Rake and Trail Calculator 2014)

Trail of a typical motorcycle, which is one of the design parameters that affect pitch-over, is shown in Figure 2.11. A motorcycle model with higher trail (Figure 2.12) has less tendency of pitch-over. However, a higher trail makes manoeuvring in crowded conditions difficult.

Figure 2. 12 Motorcycles with large trails (Las Vegas Metric Bike Fest 2006)

2.14 Method available to prevent pitch-over

There are researchers around the world working on development of effective braking systems and some of the research outcomes are implemented in brake systems. Anti-lock braking system (ABS) is one popular braking technology that can reduce tendency for pitch-over to a certain extent. By controlling motorcycle deceleration it can prevent load transfer towards front wheel and, hence, can reduce the tendency to pitch-over. ABS combined brake systems on motorcycles can improve braking efficiency (Clarke et al. 2007).

Rear-wheel lift-up mitigation system along with ABS also reduces pitch-over tendency. In this system, integrated pressure sensors detect rear wheel lift up by monitoring the pressure variations in tyres due to load transfer. If the system detects rear wheel lift-up, ABS adjusts front wheel brake pressure to control deceleration and reduce load transfer towards front wheel (Giombini and Vecchi 2008).

2.15 Disadvantages of available pitch-over avoidance techniques

In some driving conditions like wet or icy roads, ABS increases stopping distance, which is very critical in panic braking condition (Ouellet and Vira Kasantikul 2006). The cost of ABS equipped vehicle is marginally higher than that of a non-ABS vehicle (Jost et al. 2006). ABS starts working only when brakes are applied at a minimum operating speed. Repair and maintenance of ABS is high compared to a normal braking system (Jost et al. 2006). Over confidence of motorcycle rider on motorcycles with ABS can lead to an accident. Sometimes ABS can cause problem by messing up with the functioning of brakes components (Jost et al. 2006). Also, while braking disorientation of ABS with a compensating brake sensor can cause motorcycle to shudder and make loud noise. This condition can confuse the rider and make braking worse. In addition, ABS is not very effective in braking during cornering events (David et al. 2004).

2.16 Identified gaps in literature

A modern motorcycle is fitted with several active safety systems in one or the other form. When an active safety system is implemented in a vehicle, driver adaptation to the system or the risk elimination because of the system, is mostly undefined. Following questions need to be asked always to assess the effectiveness of any safety equipment.

- What kind of accidents can be avoided by active safety systems?
- On what type of road conditions can a vehicle be stable?
- How does an active safety system function with different driving styles?
- How does an active safety system function under different road condition and weather?

Effectiveness and performance of active safety system depends very much on driving behavior. Physical study of driving must be conducted to understand different driver style. Effective utilisation of active system is possible only when the driver is systematically educated in the use of such system. Development of a control concept which will sense driver input and tune the vehicle for his style is a future development.

Motorcycle handling behaviours is an interesting subject to the researchers and most of these behaviours are yet to be studied in depth (Elizabeth et. al. 2001). Results from various studies so far have to be implemented and need to elaborate a study on handling behaviours of motorcycle (Elizabeth et. al. 2001). Rider influence on the handling behaviour of motorcycle is very critical element. Rider posture, leaning, centre of gravity location etc. have to be considered for virtual testing of motorcycle for its handling behaviour. Today various analysis tools are available with the rider model built in for conducting motorcycle handing behaviour test (Limebeer, Sharp and Evangelou 2001).

As the rider training for the collision avoidance or effective braking technique does not result in much improvement in reduction of accidents, it is recommended to have a control system built into the motorcycle that, if it does not eliminate, at least reduces rider intervention required. In most of the accidents, riders have less than 2 seconds to execute all pitch-over avoidance actions. However, it has been found that riders fail to make use of many techniques taught to them during training. A pitch-over avoiding action has to be executed successfully within limited available time from the time pitch-over is expected by the rider. In most cases, this is not possible without the help of an automatic control system that can do the collision avoidance action by sensing the driving conditions (Elizabeth et. al. 2001).

Extensive research has been, and continues to be, conducted to prevent instability caused by panic manoeuvring without taking into consideration the effect of rider response on the phenomenon. As far as author's reference and data collection is concerned very little work is reported on pitch-over dynamics study (Sharp and Limebeer 2001). This work will be a big progress in motorcycle safety, and provided a true foundation for further research (Gillespie 2006). Development of a control system that, despite inappropriate actions by the rider in a panic situation, can provide stability to motorcycles will go a long way to reduce accidents (Singh 2007). In India, the coarseness of data in accident statistics, in terms of types of accidents, conditions, causes etc., makes it impossible to estimate the proportion of pith-over accidents. However, observation of driving conditions and patterns sharp braking to avoid numerous obstructions, one can only project that the proportion of pitch-over accidents will be quite high. Read the suggested alternative and if it sounds correct, replace the existing one with it.

2.17 Proposed Research

Chances for motorcycle accidents are about 30% more compared to car accidents. But very little research has been conducted on the motorcycle accident causes (Pein 2004). The objectives arrived for proposed research are framed so as to acquire a better and detailed understanding of the pitch-over phenomenon in motorcycles due to panic manoeuvre/braking. Also to propose possible parameters that can influence the pitch-over in their threshold values. This work will help the motorcycle manufacturers to develop a pitch-over preventing mechanism and implement into their products.

Chapter - 3: Research Methods and Methodology

3.1 Introduction

As this work uses virtual simulation to obtain results, numerical methods used and models involved are of predominant importance for obtaining valid solution. Initially theoretical equivalent of selected motorcycle was modelled in order to study its dynamics during braking.

In this chapter development of mathematical and ADAMS simulation models has been described. Mathematical model used to validate the motorcycle braking and load transfer behaviour theoretically is later used for verifying ADAMS model. During hard braking condition vertical load acting on rear wheel becomes zero due to load transfer and it initiates pitch-over of motorcycle. Mathematical model helped to understand pitch-over behaviour of motorcycle during braking.

Figure 3. 1 Influence of overall braking force coefficient on non-dimensional loads on wheels (Cossalter 2006)

Figure 3.1 shows theoretical pitch-over condition. In this figure braking force coefficient is plotted along X-axis and dynamic load ratio along Y-axis. Under panic braking condition, as braking effort on the front brake increases, dynamic load causes reduction of reaction force on the rear wheel. When 100% of braking effort is on front wheel, reaction force on rear wheel becomes zero. During this condition, braking force coefficient is 1 and load acting on front wheel is equal to the overall weight of the motorcycle. At a point where the motorcycle falls forward, braking force vector and dynamic load vector will be passing through the centre of gravity of the motorcycle. Pitch-over trigger point of a motorcycle can be calculated using equation 3.6.

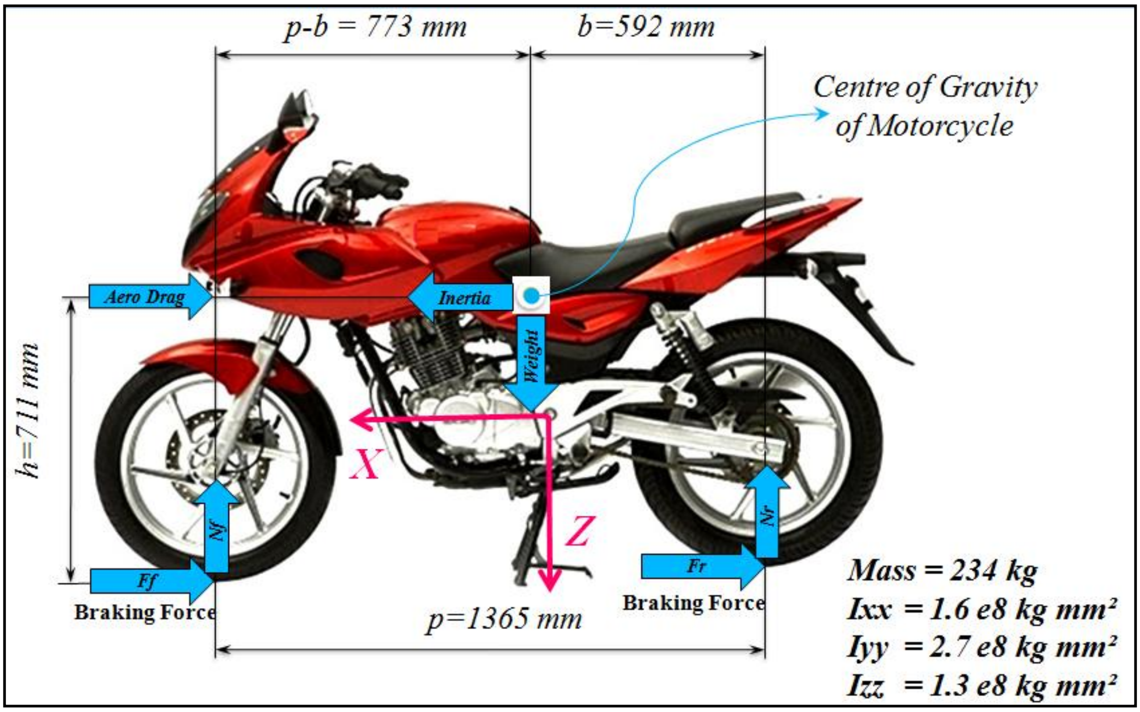

Figure 3. 2 Key geometric parameters for study of dynamics of a motorcycle

Figure 3.2 shows a motorcycle with key geometric parameters, dynamic forces acting during motion and location of centre of gravity. *p*, the distance between front and rear wheel contact point is known as wheelbase. h is the height of the centre of gravity from wheel contact point. b is the horizontal distance between the centre of gravity location to the rear wheel contact point. *FD* is aerodynamic drag, $m\ddot{x}$ is inertia force and *mg* is weight of motorcycle. Resulting ground reactions in the vertical direction to these loads at the front and rear wheel contact points are N_f and N_r respectively. F_f and F_r are the frictional forces acting on the front and rear wheel respectively. N_f is the sum of the static load and the load transfer, N_r is difference between the static load and the load transfer is the dynamic load on the rear wheel.

For the motorcycle under dynamic condition, equations of equilibrium involving the forces described above, and their moment about the centre of gravity of the motorcycle, can be written as

$$Equilibrium\ of\ horizontal\ forces : m\ddot{x} = -F_f - F_r \tag{3.1}$$

$$Equilibrium\ of\ vertical\ forces: mg - N_r - N_f = 0 \tag{3.2}$$

$$Equilibrium\ of\ moments\ around\ the\ center\ of\ gravity:$$

$$-Fh - N_r b + N_f(p - b) = 0 \tag{3.3}$$

From moment equilibrium condition, total braking force F, sum of F_f and F_r, can be calculated (Equation 3.4). At the point of pitch-over, low value of dynamic load N_r on the rear wheel indicates enhanced tendency for motorcycle to pitch-over and N_r=0 defines the onset of pitch-over.

$$F = N_f \frac{(p-b)}{h} = mg \frac{(p-b)}{h} \tag{3.4}$$

The above equation during pitch-over can be written as,

$$m\ddot{x} = -F = -mg \frac{(p-b)}{h} \tag{3.5}$$

where $\ddot{x}$ is the maximum deceleration and is directly proportional to (p-b), and inversely proportional to h.

$$\frac{\ddot{x}}{g} \leq \frac{p-b}{h} \tag{3.6}$$

Equation 3.6 is the condition where motorcycle does not pitch-over. In this scenario ratio of motorcycle deceleration and acceleration due to gravity will always be less than or equal to the ratio of distance between the centre of gravity location to the front wheel contact point and the height of the centre of gravity. Equilibrium of moments about the centre of gravity is maintained in this scenario. The tendency to pitch-over is independent of the size of the motorcycle and dependent only on the geometric proportion and load distribution in the motorcycle. Hence, weight of the motorcycle has influence on the deceleration but no influence on pitch-over limit. Tendency for a motorcycle to pitch-over depends on the position of the centre of gravity. Motorcycle with high and forward positioned centre of gravity will have higher tendency to pitch-over. Hence, by keeping the centre of gravity as low as possible and/or towards the rear end of the motorcycle, tendency for pitch-over can be reduced.

3.2 Load transfer during acceleration and braking

Inertia forces generated during acceleration and braking change wheel reaction forces under static equilibrium. During acceleration, weight of motorcycle gets transferred to the rear wheel of motorcycle. As a result, vertical force on the rear wheel increases. Similarly, during braking, inertia force due to braking is transferred to the front wheel and the vertical force at the front wheel increases.

3.3 Motorcycle braking and load transfer

Using below equations (3.7 and 3.8) given below, dynamic loads acting at the wheel contact points of a motorcycle during braking can be calculated.

Dynamic load acting on the front wheel

$$N_f = mg\frac{b}{p} + F\frac{h}{p} \Rightarrow F = mg\frac{(p-b)}{h} \tag{3.7}$$

Dynamic load on the rear wheel

$$N_r = mg\frac{(p-b)}{p} - F\frac{h}{p} \tag{3.8}$$

From equation (3.7 and 3.8) it is evident that load transfer $F\frac{h}{p}$ during deceleration is directly proportional to the overall braking force F and the height of the centre of gravity and inversely proportional to the wheel base. The above relation is a design condition to be maintained while designing a motorcycle to avoid pitch-over during braking.

In addition to geometrical parameters identified above, tendency for pitch-over is also affected by operational parameters. Some of those can enhance and some of those can diminish the tendency of a motorcycle to pitch-over. Identification and study of their effect on pitch-over is difficult to carry out analytically. For this purpose, in this work, multi-body dynamics simulation software ADAMS has been used.

ADAMS was used as an alternative to testing as testing is costly and not feasible for various test conditions. ADAMS allows modelling of operational conditions with few approximations and provides accurate results. Also, using ADAMS it is possible to model and simulate extreme conditions because it is not limited by safety considerations. ADAMS models provide a better control of parameters than in tests as no human input is involved. Motorcycle model in ADAMS was validated to a higher accuracy compared to analytical models for its design and operational parameters. This virtual motorcycle model yields more realistic results as it simulates dynamic behaviours of a motorcycle and resulting contact forces, inertias, moments close to a real life condition. Motorcycle simulation in ADAMS is very cost effective compared to a testing for iterative design approach and more realistic compared to an analytical approach. By using virtual simulation it is possible to include maximum operating parameters as well as the extreme operating condition such as very high velocities, sudden braking and manoeuvring that are not possible for a normal test facility or a human rider during test.

Front tyre to road contact profile is a critical area while modelling a motorcycle. Traditionally, a thin walled disc shape was used to represent the tyre. However, this type of tyre model does not represent the over-turning moment property. Hence, thick type non-linear tyre model, more suitable for an MBD model of motorcycle, was used to build the motorcycle. From literature very few parametric values for MBD model of such tyre could be found. However, sufficient experimental data is available on motorcycle tyre modelling and testing. ADAMS motorcycle tyre models use such common data to identify tyre parameters while modelling motorcycle tyres (Sharp, Evangelou and Limebeer 2004). For this study, Pacejka tyre models (Pac2000) were used. As in this work simulation of only linear braking was involved, complex properties of the tyre model were of little benefit.

All new advanced technologies used in modern motorcycles are to enhance active safety of the vehicle. Tools available for developing motorcycle dynamics are very few. Most of the tools available deal only with linear simulation models with limited degrees of freedom. In such tools, compliances in the suspension systems are not included and tyre behaviour is considered as linear. However, ADAMS motorcycle module allows inclusion of the above critical parameters. ADAMS uses non-linear tyre models and allows users to include complex control systems. Complex equations of motion are easily investigated by ADAMS (Pruckner and Breuer 2000).

3.4 Development of MBD model for Motorcycle

A Multi-Body Dynamics (MBD) model of motorcycle was developed. This model was used to carry out parametric studies to identify parameters critical to pitch-over phenomenon.

Motorcycle selected for this study was Bajaj Pulsar. It is one of the highest selling motorcycles in India and South East Asia. Most of the motorcycles launched in India and south East Asia today have power and technical specifications similar to that of Bajaj Pulsar. Effective means of controlling pitch-over of this type of high speed motorcycle will be of considerable benefit to its users. Hence, this problem is a critical issue for motorcycle researchers and developers. Technical specifications for Bajaj Pulsar are given in Table 3.1.

Table 3. 1 Technical Specifications of Bajaj Pulsar

Kerb Mass	146 kg
Length	2095 mm
Width	750 mm
Height	1100 mm
Wheelbase	1340 mm
Seat Height	790 mm
Static CG	(96.6, -0.3, -155.8 mm)
Body	
Frame	Advanced Design Diamond Frame
Front Suspension	Telescopic
Rear Suspension	Spring-Damper Normal
Front Tyre	2.75 x 18"
Rear Tyre	3.00 X 18"
Front Brake Type	240 mm Disc
Rear Brake Type	130 mm Drum
Engine & Transmission	
Net Power	13.3 BHP @ 8000 rpm (9.9 kW)
Torque	1.3 kg-m @ 5500 rpm (12.8 Nm)

Front suspension in the selected motorcycle is a telescopic type with spring-damper system included. ADAMS model of this front suspension is shown in Figure 3.3. It was modelled using spring damper system in ADAMS and properties associated to spring and damper is given in the model. This was connected to the motorcycle assembly using a revolute joint at the handlebar centre point. Handlebar was fixed to the front suspension using a fixed joint.

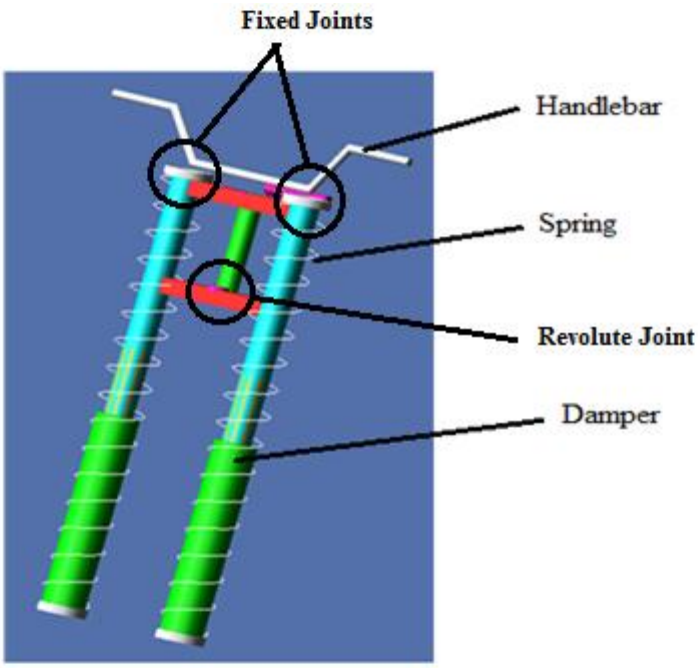

Figure 3. 3 ADAMS model of front suspension of Bajaj Pulsar motorcycle

Bajaj Pulsar has a swing arm type rear suspension with spring-damper system. It was modelled using spring damper system associated to a swing arm part in ADAMS and properties associated to spring and damper was given in the model. Figure 3.4 shows the model of the rear suspension. Rear suspension was connected to the motorcycle assembly using a revolute joint at the swing arm centre point. Swing arm was fixed to the rear suspension using a fixed joint on bottom end of both the spring damper.

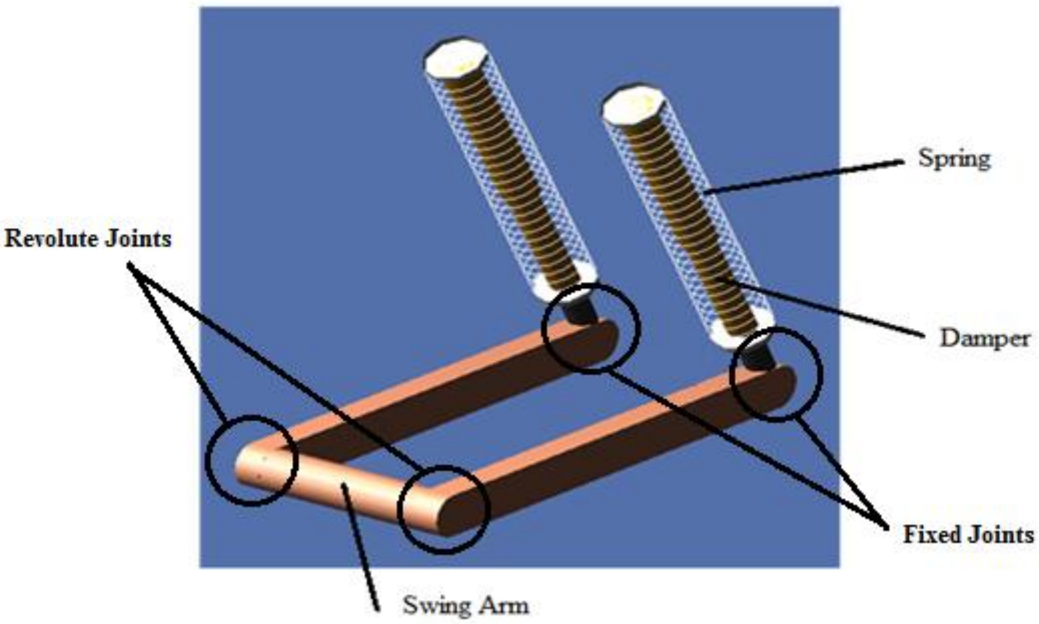

Figure 3. 4 ADAMS model of rear suspension of Bajaj Pulsar motorcycle

Assembly model of the motorcycle was constructed with subsystems like, front suspension, rear suspension, handle bar, main frame, front wheel with brake systems, rear wheel with brake systems, power train systems and a solid rider dummy. Geometrical CAD models of these subsystems were created for building ADAMS model. Front wheel with brake systems was connected to the front suspension through a revolute joint. Similarly, the rear wheel with brake systems was connected to the rear suspension through a revolute joint. Power train systems were connected to the rear wheel using a chain function.

Figure 3.5 shows the complete motorcycle assembly with rider in ADAMS. Motorcycle frame, suspension parts, rider dummy and handle bars were constructed using CAD geometry. Suspension springs and dampers use property files that carry functional behaviour of the systems in ASCII format. Tyre property files were used to represent the tyre models and power train subsystems in motorcycle.

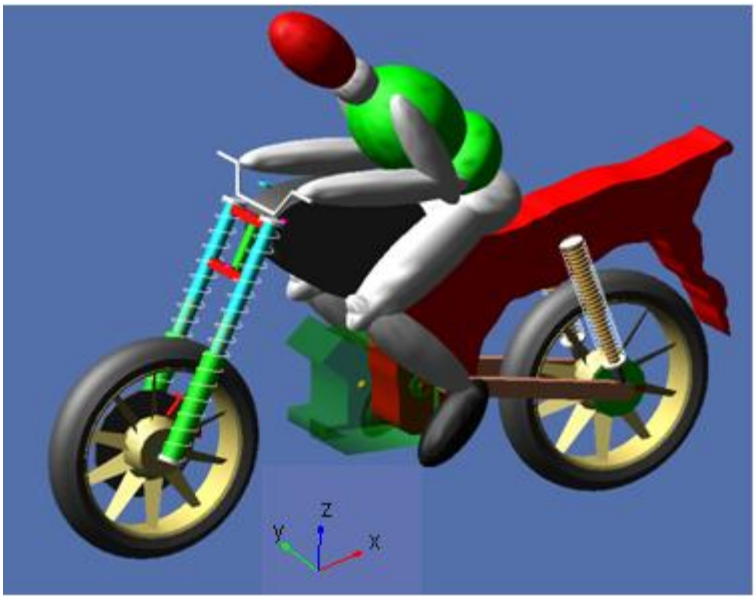

Figure 3. 5 Model of motorcycle assembly in ADAMS

Masses and centre of gravity locations of individual subsystems with respect to the vehicle co-ordinate system of the motorcycle are given in Table 3.2. Values of masses were compared with physical parts of the modelled motorcycle and the locations of the centre of gravity were obtained from the geometric model of the complete motorcycle.

Table 3. 2 Motorcycle subsystem mass and centre of gravity location

Description	Mass (kg)	Centre of gravity location of subsystems		
		X (mm)	Y (mm)	Z (mm)
Handlebar	2.4	449.6	1.3	575.0
Headlamp	5.1	667.8	2.7	441.8
Fork Upper	6.8	605.0	0.0	354.5
Fork Lower	4.5	25.2	0.0	128.9
Frame	39.7	31.8	7.8	212.7
Front Wheel	9.3	850.0	8.7	127.4
Rear Wheel	12.7	514.3	8.9	87.3
Swing Arm	6.9	321.0	3.3	53.7
Rear Shocker-Upper	1.2	331.4	1.3	181.8
Rear Shocker-Lower	2.9	376.5	1.5	69.7
Engine and Silencer	38.8	143.5	41.4	24.0

Locations of the centre of gravity of the motorcycle, with and without a rider weighing 70 kg, are shown in Figures 3.6 and 3.7 respectively. The centre of gravity locations were obtained from geometric model.

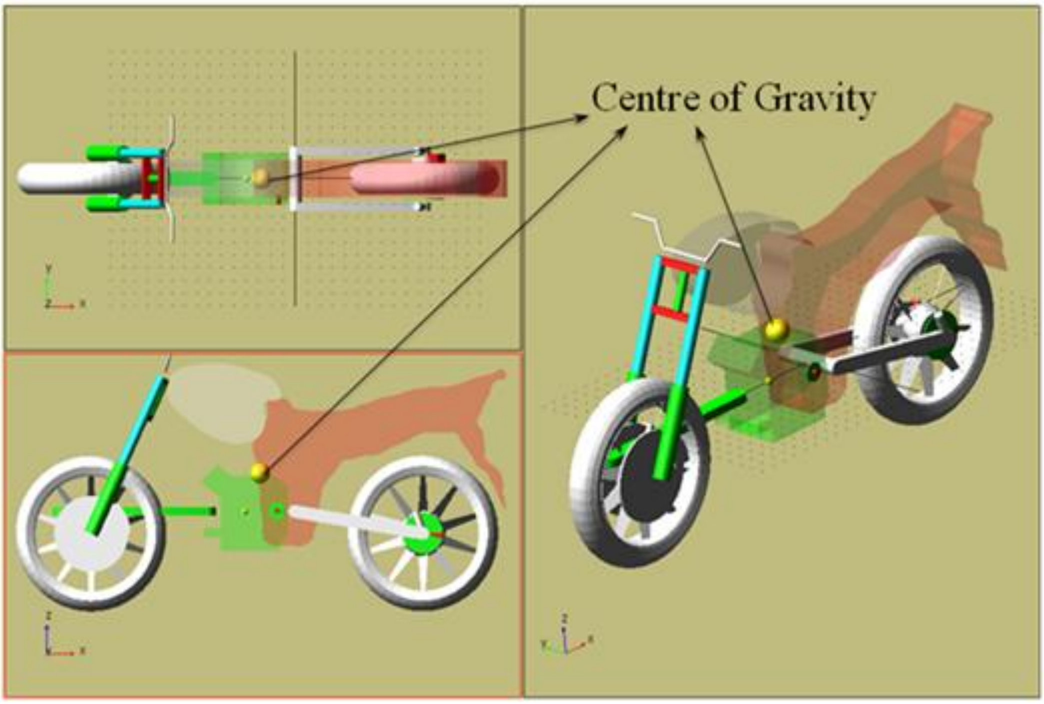

Figure 3. 6 Centre of gravity of the motorcycle without rider

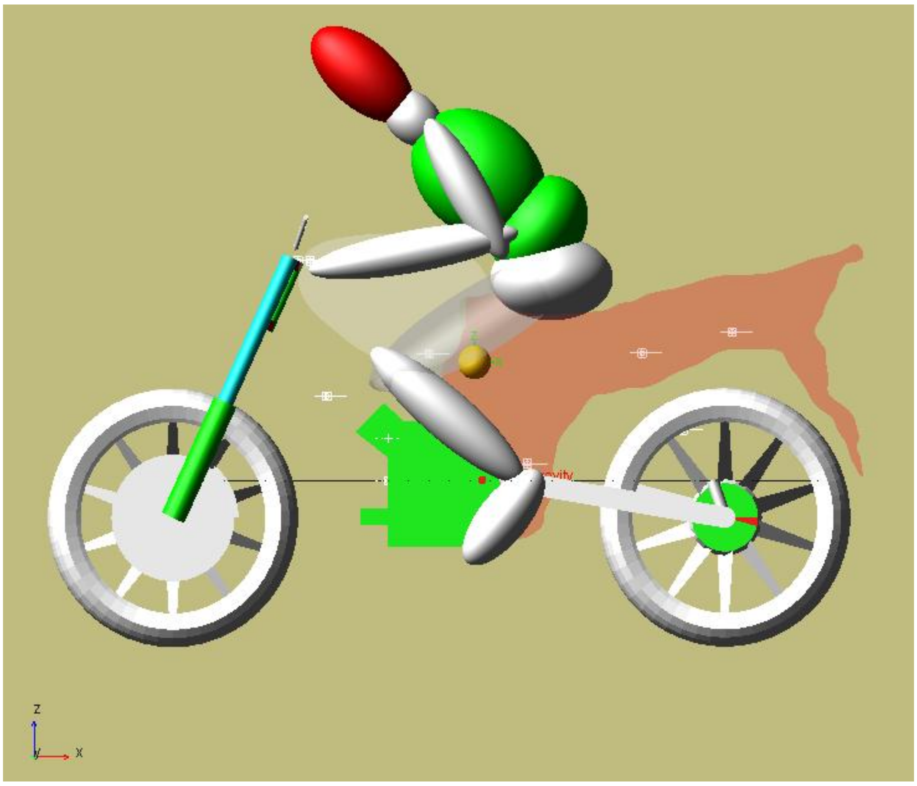

Figure 3. 7 Centre of gravity of the motorcycle with rider

Trend of shift of centre of gravity with the rider is as observed in physical measurements. A comparison of the two cases is tabulated in Table 3.3. A close correlation between the trends in the two cases can be observed in the data. A pictorial representation of the comparison can be seen in Figure 3.8

Figure 3.8 shows that when the motorcycle along with the rider is considered the height of the combined centre of gravity is higher than that of the motorcycle alone.

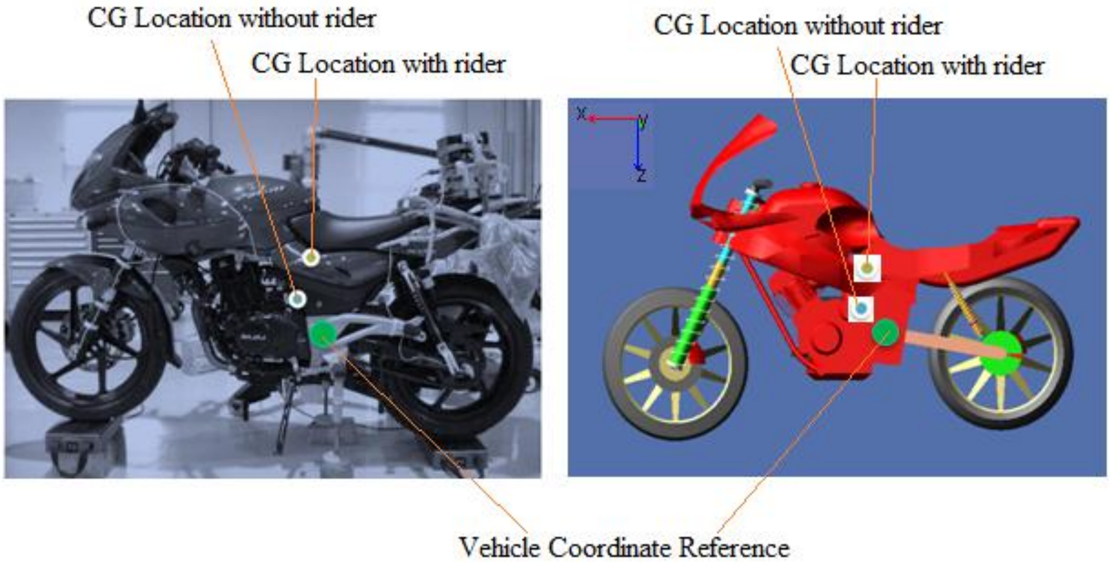

Figure 3. 8 Motorcycle co-ordinate reference and CG location

Table 3.3 shows the comparison of the location of the centre of gravity in a physical motorcycle, as measured in a laboratory and in ADAMS model. This shows a close correlation of the ADAMS model to the physical model. The model uses a rider weighing 70 kg. Comparison of the centre of gravity locations was also used to validate the ADAMS motorcycle model against the physical motorcycle. The physical centres of gravity measurements were done by a reputed two wheeler manufacturer and ADAMS measurements were obtained from ADAMS motorcycle assembly model. ADAMS model was validated to the physical model by comparing the ADAMS CG values to the physical CG values of the motorcycle.

Table 3. 3 Change in centre of gravity location under various loading

Motorcycle Loading Conditions	**X in mm**		**Y in mm**		**Z in mm**	
	Measurement	**ADAMS**	**Measurement**	**ADAMS**	**Measurement**	**ADAMS**
Centre of Gravity of the motorcycle without rider	96.6	96.3	-0.3	-0.3	-155.8	-155.2
Centre of Gravity of the motorcycle with rider of mass 70 kg	78.6	78.3	-0.3	-0.2	-318.8	-318.2

3.5 Test set-up

With close correlation observed between the static parameters, mass and location of centre of gravity of the model with the physical motorcycle, first stage of validation of model was completed. To ascertain that the model is able to duplicate the behaviour of the actual motorcycle in dynamic condition, various running and manoeuvring conditions test results were used. Tests were conducted by a reputed two wheeler manufacturer and the data was used to validate the ADAMS motorcycle model.

The tests were carried out using a motorcycle (Figure 3.9), instrumented to capture displacements at various locations. Linear Variable Differential Transformer (LVDT) were used to measure the displacement at various locations on the motorcycle. Readings from LVDT from various tests were compared with the results from ADAMS simulation for the same test and road conditions. Data processing controller systems were fixed to pillion rider seat. The overall weight of the data acquisition system is also considered for final calculation and same is compensated in ADAMS model.

Figure 3. 9 Motorcycle used for taking the measurements in testing

On the front wheel axle LVDT was mounted between lower bracket of front suspension and front wheel axle (Figure 3.10).

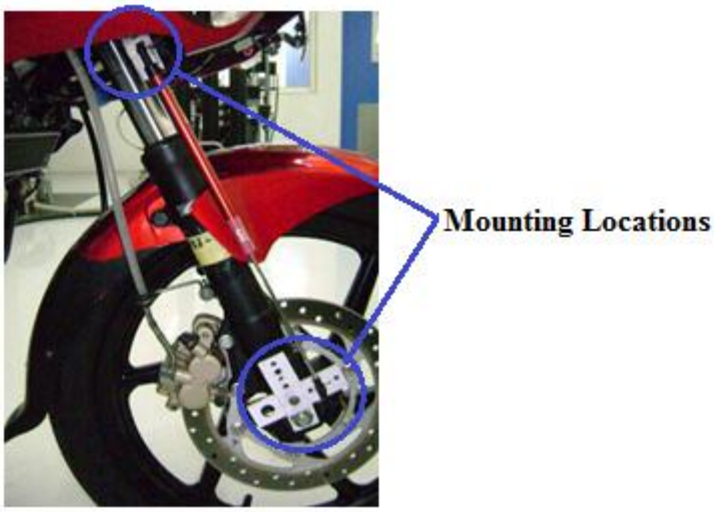

Figure 3. 10 LVDT mounted on front suspension

The arrangement of rear suspension LVDT is shown in Figure 3.11. In rear suspension also the LVDT was mounted between lower bracket and axle of rear suspension and wheel.

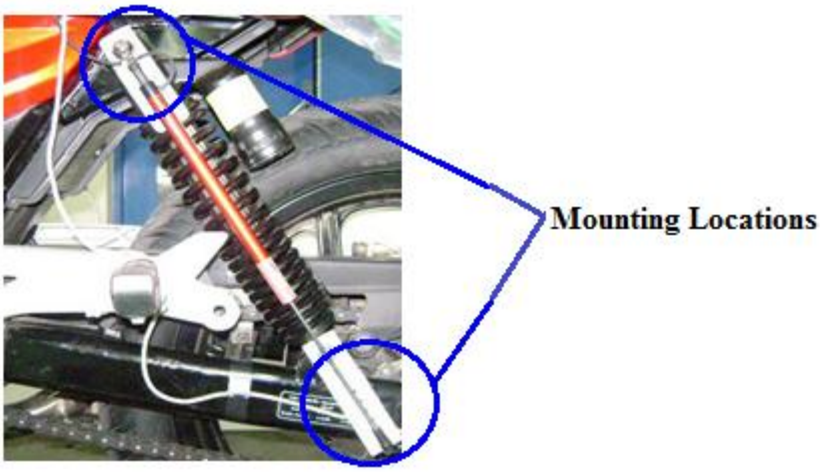

Figure 3. 11 LVDT mounted on rear suspension

Using LVDT, relative displacement between the upper and the lower end of suspension was measured. During the ride, suspension had telescopic movement and that displacement was measured in the same direction. Test results were compared with ADAMS model simulation results.

Chapter - 4: Results and Discussion

4.1 Introduction

Theoretical validation was conducted to confirm that the ADAMS motorcycle model is able to represent and correctly reproduce the dynamic behaviour of a motorcycle going through typical manoeuvres. In the first stage of validation, simulation results were compared against the results from analytical calculations. In the second stage of validation, results from physical tests were used for assessing the accuracy of the ADAMS model. In this chapter, results of these two stages of validation are presented.

In the first stage of validation study, simulation of Constant Radius Cornering (CRC) manoeuvre was used. Lateral acceleration was selected as the parameter to be used for validation. In second stage of validation study, manoeuvres like straight line braking with full braking pressure on front brake, full braking pressure on rear brake, distributed braking pressure on front and rear brake and CRC, for different operating conditions, were used. Variation of velocity with time and with distance travelled, and deflection in front and rear suspensions were used as the parameters for comparison. Limited set of values were used as these were sufficient to validation of linear behaviour of the two-wheeler.

Once ADAMS model was validated based on the comparison of its results with test results, further simulations were carried out to identify the parameters that contribute to pitching-over of the motorcycle. Effect, and extent of it, of various geometric and load parameters were categorised.

4.2 Validation of motorcycle model with analytical solutions

Results of validation of ADAMS model using analytical solutions are presented and discussed below.

4.2.1 Constant Radius Cornering (CRC)

For CRC for validation, problem of a motorcycle going around a circular track of radius 50 m at a speed of 60 km/h was used. From calculations, lateral acceleration for this was found to be 5.56 m/s^2.

$$Lateral\ acceleration = {v^2}/{r} = \frac{16.6667^2}{50} \quad = 5.56\ \mathrm{m/s^2}$$

For simulation of same CRC in ADAMS, simulation's time was set to 20 s. Road was modelled as a flat circular road. 30 m was used as entry distance before motorcycle starts following the curved path. Motorcycle in the model was modelled as going anti-clock wise on the circular track. Initial velocity was set at 60 km/h and time in which motorcycle start taking turn was 2 seconds. Result of the simulation (Figure 4.1) shows that lateral acceleration in the steady state turning calculated by the model is 5.56 m/s^2. This, up to 2 places of decimal, is same as analytically predicted value.

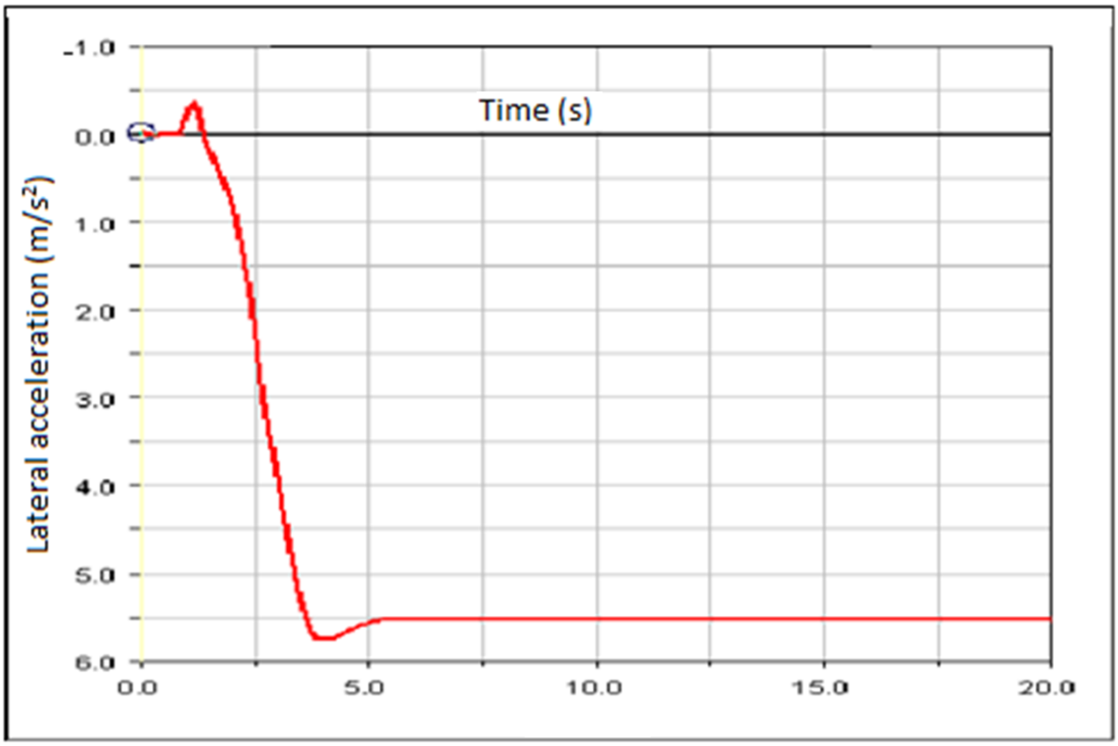

Figure 4. 1 Lateral acceleration of motorcycle at 60 km/h on 50 m CRC track

4.3 Validation of motorcycle model with test results

In the second stage of validation, for more rigorous validation of ADAMS model, a set of test data, for three different braking proportioning, was obtained from a motorcycle manufacturer. The three conditions of straight line braking used were of 100% braking effort on the front brake, 100% braking effort on the rear brake and 50% braking effort on each - the front brake and rear brakes. In addition to that, simulation results were also validated with acceleration along a straight line.

There are few tests that are highly subjective because the driver's braking action during the test is very important. Braking events and various manoeuvring events in physical tests are subjective and the co-relation depends on physical driver behaviour during the test.

4.3.1 Velocity change during braking

In this case initial velocity of the motorcycle was set at 50 km/h and 100% braking effort was applied on the front brake. Variation of velocity of motorcycle with time, from ADAMS simulation, was compared with the test results (Figure 4.2). It can be seen that ADAMS model is able to get stopping distance very close to the test. In case of velocity, it is able to match the trend observed in the test. The magnitude of velocity fluctuates but the maximum difference at any point of time is within 10%. Considering the variation attributable to manual inputs in testing this can be considered as acceptable.

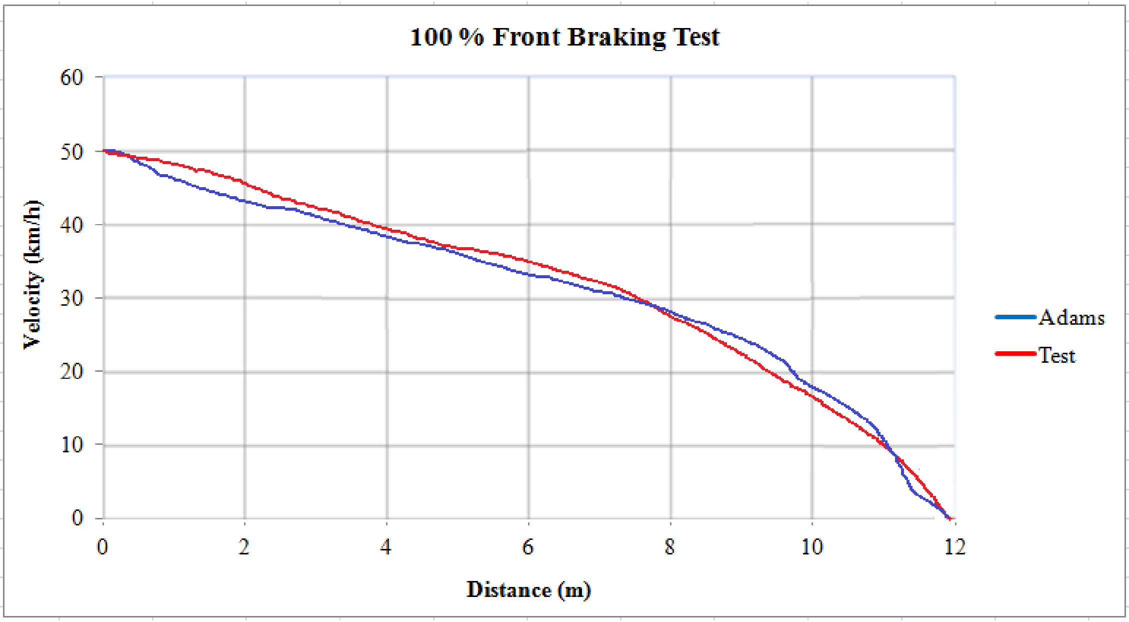

Figure 4. 2 Motorcycle deceleration characteristics with full braking effort applied on front brake

Figure 4.3 shows the comparison of velocity results from test and ADAMS simulation for second case of braking test. During this test initial velocity of the motorcycle was set at 50 km/h and 100% braking effort was applied on the rear brake. In case of velocity, it is able to match the trend observed during test. The magnitude of velocity fluctuates but the maximum difference at any point of time is within 14%.

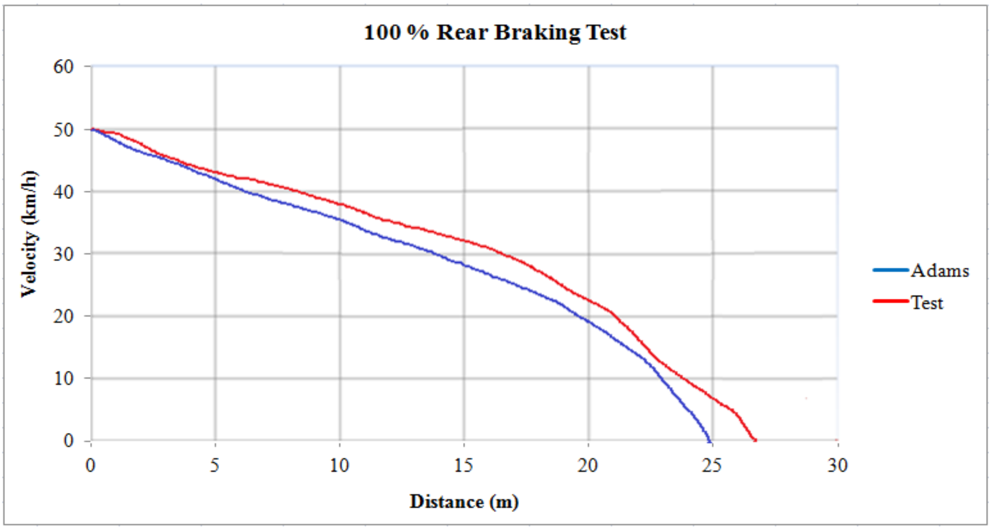

Figure 4. 3 Motorcycle deceleration characteristics with full braking effort applied on rear brake

Figure 4.4 shows the comparison of velocity results from test and ADAMS simulation for the third case of braking test. During this test initial velocity of the motorcycle was set at 60 km/h and 50/50 ratio of front brake and rear brake is applied to bring the vehicle to rest. In case of velocity, it is able to match the trend observed during test. The magnitude of velocity fluctuates but the maximum difference at any point of time is less than 11%. For this test, based on the test practice of a reputed two-wheeler manufacturer, initial velocity of 60 km/h was used.

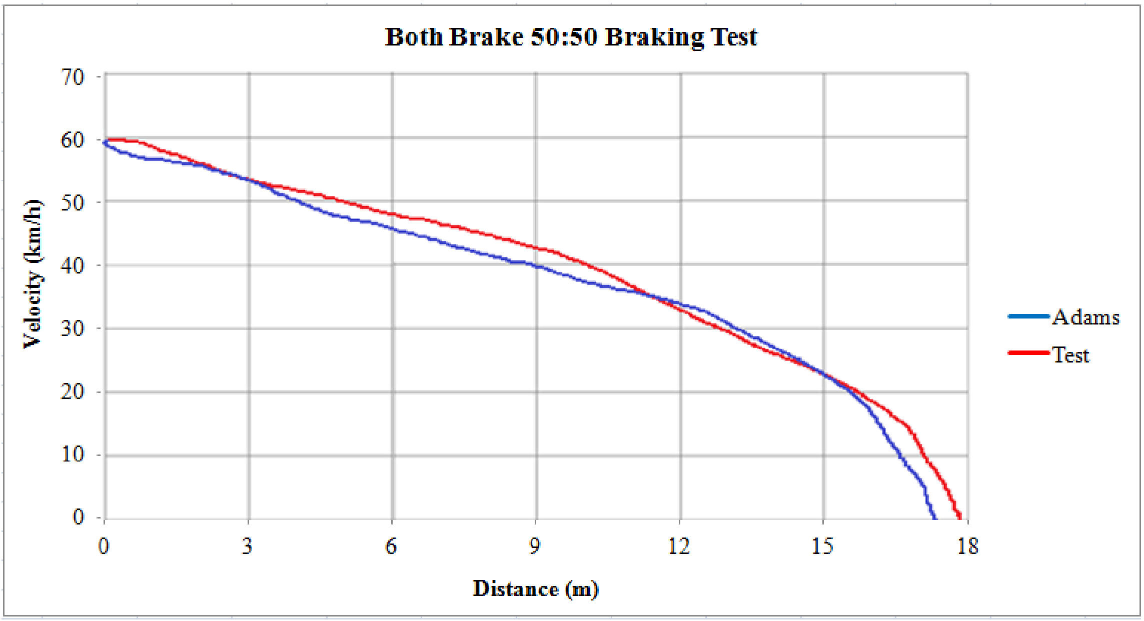

Figure 4. 4 Motorcycle deceleration characteristics with equal braking effort applied on front and rear brakes

4.3.2 Suspension displacement during braking

Figure 4.5 shows the comparison of test and simulation results of time history of velocity and displacement of front and rear suspension in a road test with brake application only on the front brake. Close correlation of the front and rear suspension displacement in test and ADAMS simulation can be observed. In case of displacement, it is able to match the trend observed during test. The magnitude of velocity fluctuates but the maximum difference at any point of time is within 7%.

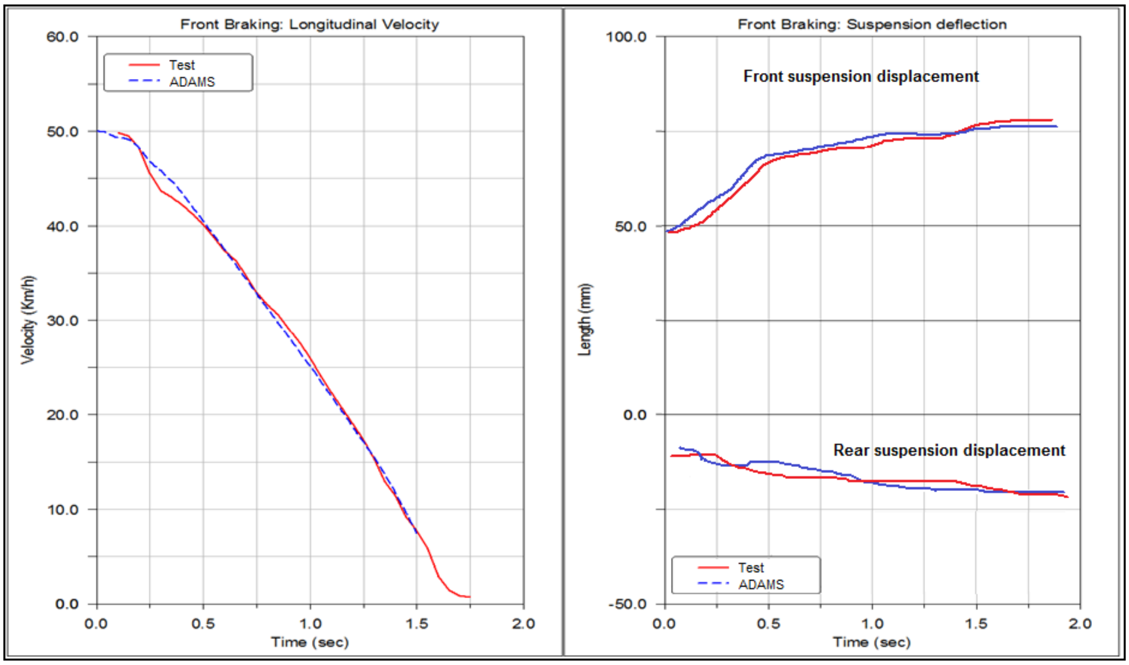

Figure 4. 5 Longitudinal velocity and suspension deflections history with full braking effort applied on front brake

Figure 4.6 shows the comparison of test and simulation results of time history of velocity and displacement of front and rear suspension in a road test with brake application only on the rear brake. Close correlation of the front and rear suspension displacement in test and ADAMS simulation can be observed. In case of displacement, it is able to match the trend observed during test. The magnitude of velocity fluctuates but the maximum difference at any point of time is within 12%.

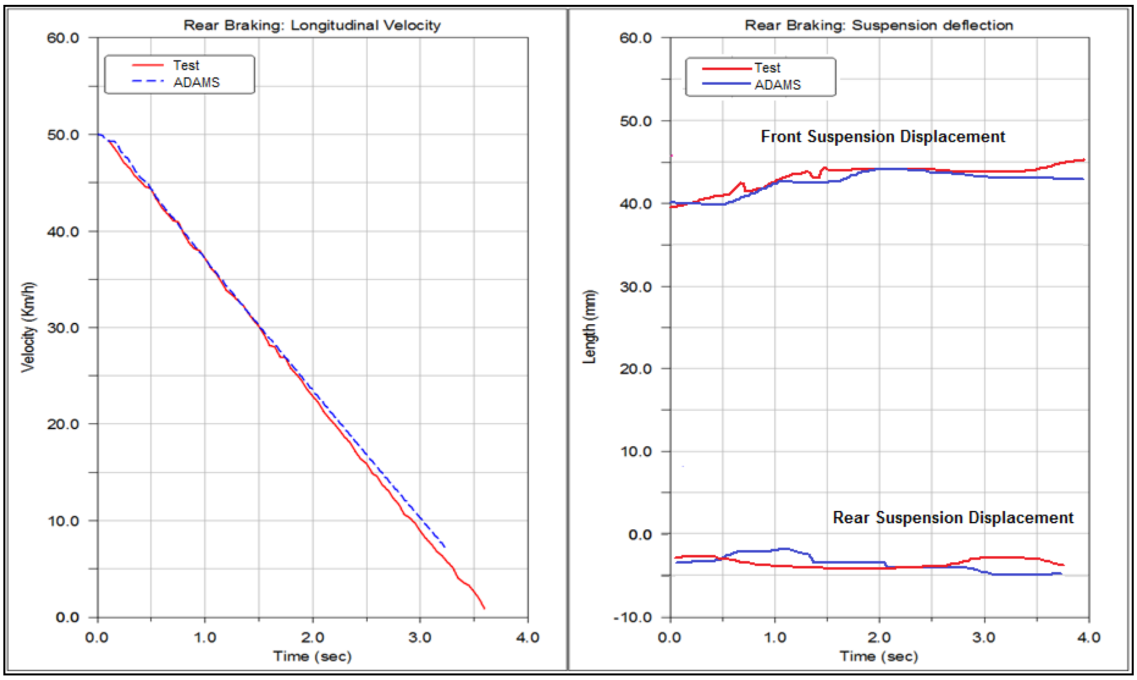

Figure 4. 6 Longitudinal velocity and suspension deflections history with full braking effort applied on rear brake

Figure 4.7 shows the comparison of test and simulation results of time history of velocity and displacement with equal braking effort applied to the front and rear brakes. Using LVDT the relative displacements of the moving and stationary halves of the front and rear suspension were measured and compared with ADAMS simulation results. The comparison of results of braking test against the ADAMS simulation shown matching for its trend and its values were within 5 to 10 % of deviation.

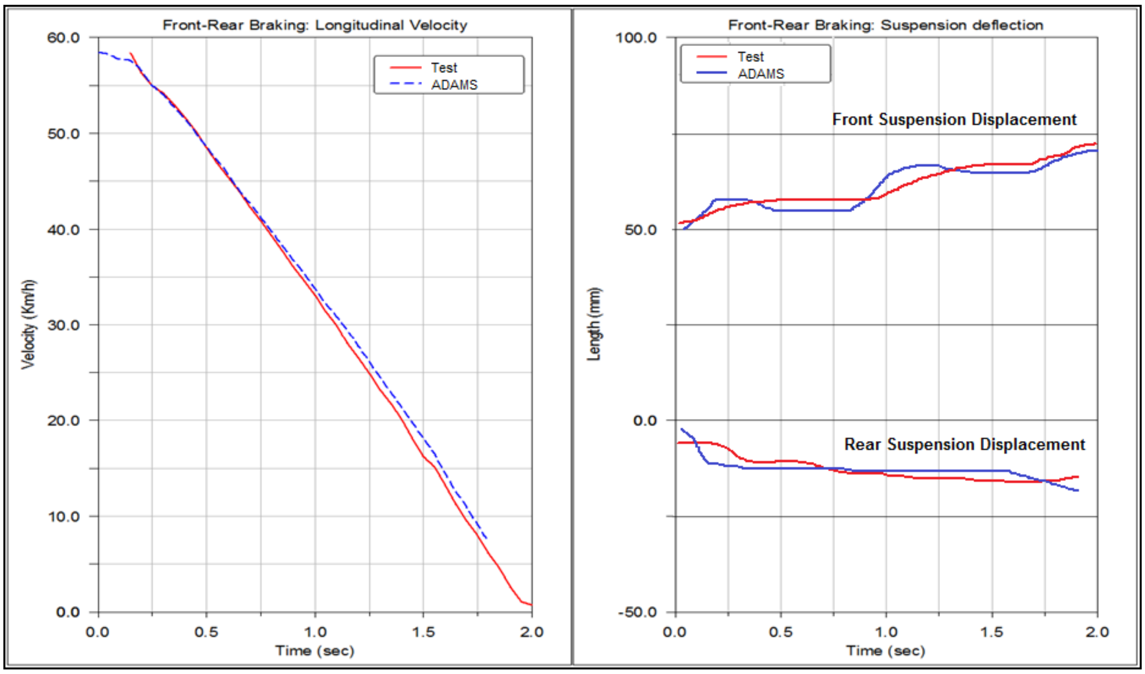

Figure 4. 7 Longitudinal velocity and suspension deflections history with equal braking effort applied on front and rear brakes

4.3.3 Acceleration test

Objective tests like acceleration test and straight line events also show very good correlation between test and simulation results. Figure 4.8 shows the longitudinal velocity of motorcycle when a straight line acceleration test conducted for motorcycle accelerating from 0 to 100 km/h.

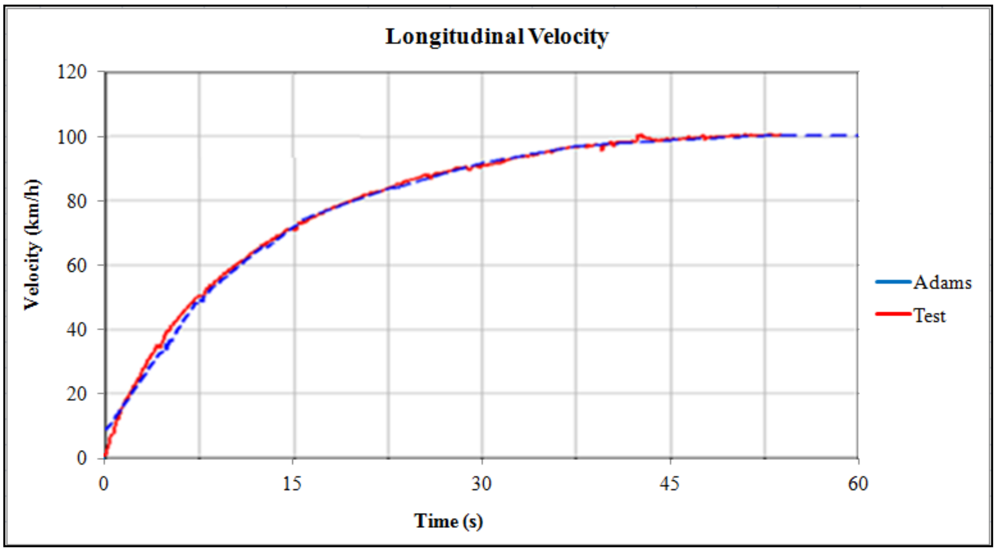

Figure 4. 8 Longitudinal velocity of motorcycle during straight line acceleration

Figure 4.9 shows the longitudinal velocity of motorcycle for a straight line acceleration test conducted in 3rd gear from 0 to 80 km/h.

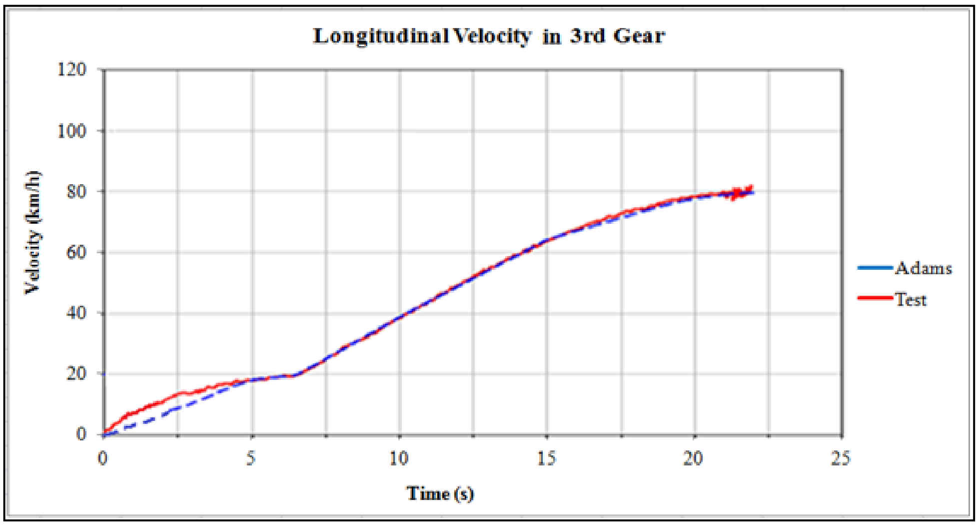

Figure 4. 9 Longitudinal velocity of motorcycle during straight line acceleration in 3rd gear

Figure 4.10 shows the comparison of engine RPM of motorcycle, from test and simulation, for a straight line acceleration test in 3rd gear.

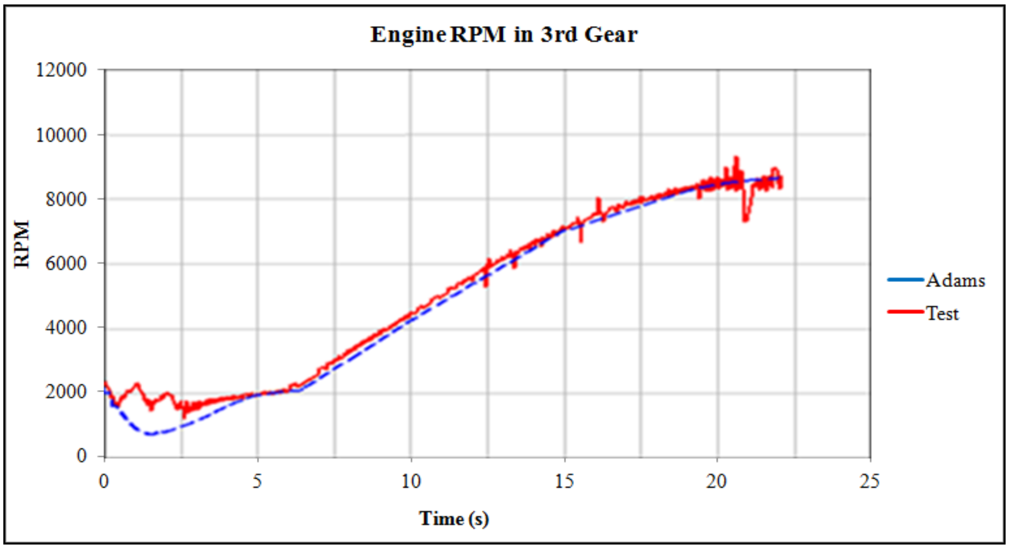

Figure 4. 10 Engine RPM of motorcycle during straight line acceleration in 3rd gear

4.4 Simulations of pitch-over phenomenon

Having validated ADAMS model, the next step was to use it to simulate pitch-over phenomenon and then study the effect of various parameters on the tendency for the motorcycle to pitch-over. Model validation results presented in the previous section show that the ADAMS model is able to capture key dynamic parameters during braking phenomena. Based on this finding the same model was used for modeling pitch-over during panic braking.

Based on some analytical work and information from the literature, variables like vehicle speed, braking duration, brake bias, road gradient and road tyre friction coefficient were identified as key parameters affecting propensity of a motorcycle to pitch-over. These parameters influence braking efficiency and, hence, deceleration of motorcycle during braking.

For carrying out this parametric study typical realistic ranges for the selected parameters were set. Boundaries for vehicle speed were set at 40 km/h and 110 km/h. These speeds can be achieved in normal riding condition. 1 to 5 seconds was set as the range of braking duration - time taken to bring the vehicle from its initial velocity to rest. Brake bias, measure of the proportion of total braking effort applied to the front wheel, was varied from 0% to 90% in steps of 10%. Road was assumed to be flat and its gradient was assumed to be 0º (flat, level road). Road tyre friction coefficient was taken as 0.7. Simulations were carried out using the combination of the parameters shown in Table 4.1.

Table 4. 1 Matrix of parameter used to study stability envelope of motorcycle

Vehicle Speed (km/h)	Braking Duration (s)	Brake Bias (%)	Road Gradient (°)	Road Tyre Friction Coefficient (μ)
40	1	0	0	0.7
50	2	10	0	0.7
60	3	20	0	0.7
70	4	30	0	0.7
80	5	40	0	0.7
90		50	0	0.7
100		60	0	0.7
110		70	0	0.7
		80	0	0.7
		90	0	0.7
		100		

Using the Table 4.1 parameter matrix, a series of simulations were carried out for various braking events. The stability and control capability of motorcycle were calculated from the results of these simulations. Influence of each parameter mentioned in Table 4.1 and its contribution to motorcycle pitch-over during braking events were studied.

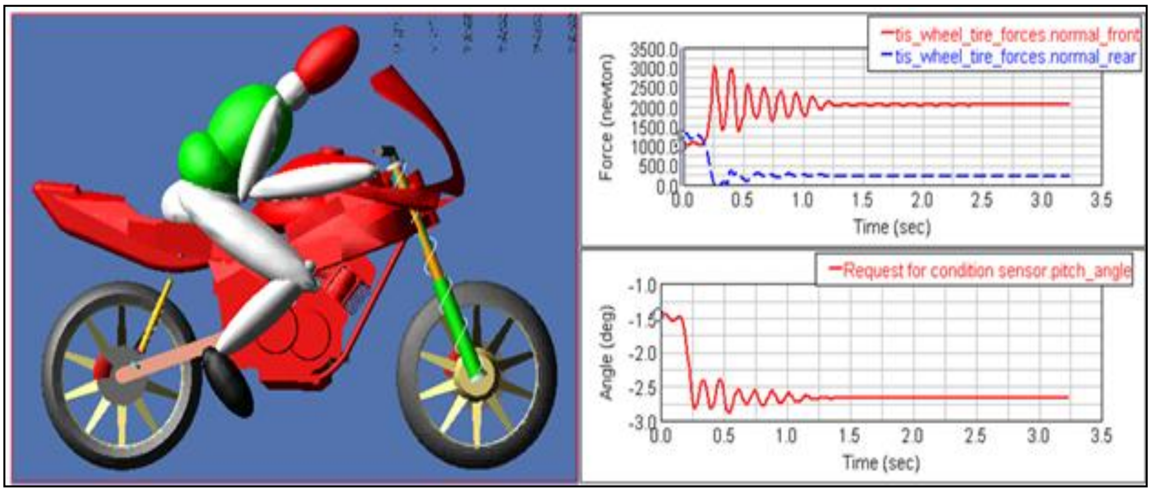

Figure 4. 11 Vertical force on wheels and pitch angle during braking

Result of a normal braking simulation where the pitch-over was not observed is shown in Figure 4.11 shows. In this simulation the vehicle was running at 100 km/h and brake force was applied in 60-40 ratio on the front and rear brakes respectively to bring the motorcycle to rest.

In Figure 4.11 it is seen that the normal (reaction) force on rear tyre always remains positive and never reaches zero. Also, the magnitude of pitch angle, the angle of flip over of motorcycle from its horizontal plane, never crosses 2.8º. This is very small compared to magnitude of pitch angle of 30º required for the motorcycle to pitch over. Threshold of 30º for magnitude of pitch angle was obtained from a series of simulations where the motorcycle used to come back to the original position if the magnitude of pitch angle was below 30º and it used to go unstable when the magnitude of pitch angle was above 30º.

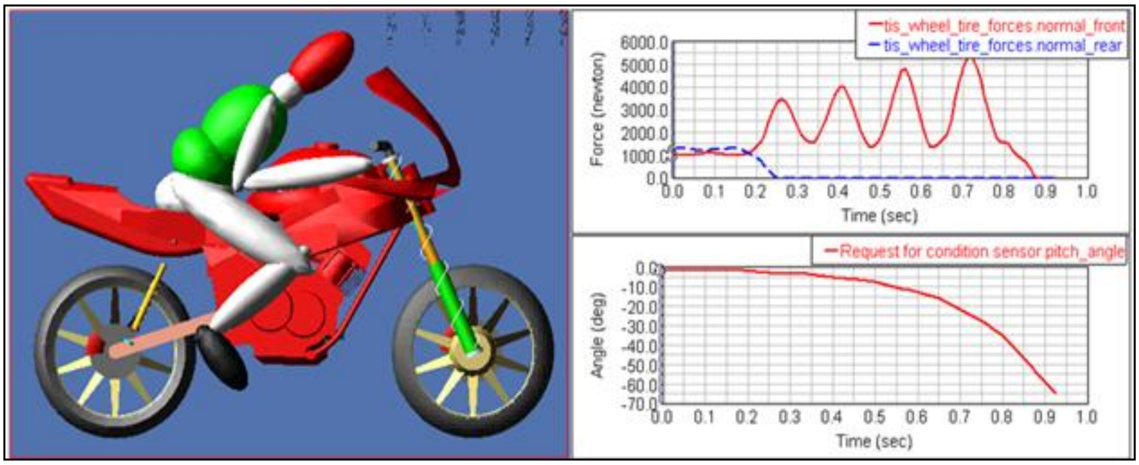

Figure 4. 12 Motorcycle braking in which pitch-over was observed

Figure 4.12 shows simulation result where the pitch-over was observed. In this test the vehicle was running at 100 km/h and 100% of brake effort was applied to the front brake to bring the motorcycle to rest. In Figure 4.12 it is seen that the rear tyre normal force is becoming zero after 0.25 seconds. Also, the magnitude of the pitch angle increased to 70º indicating a sure possibility for pitch-over.

4.5 Influence of various parameters on pitch-over

Influence of various design parameters on pitch-over of motorcycle is presented in Table A.1 (Appendix-A). A little description of the parameters and conditions for which these results are have been obtained are presented here.

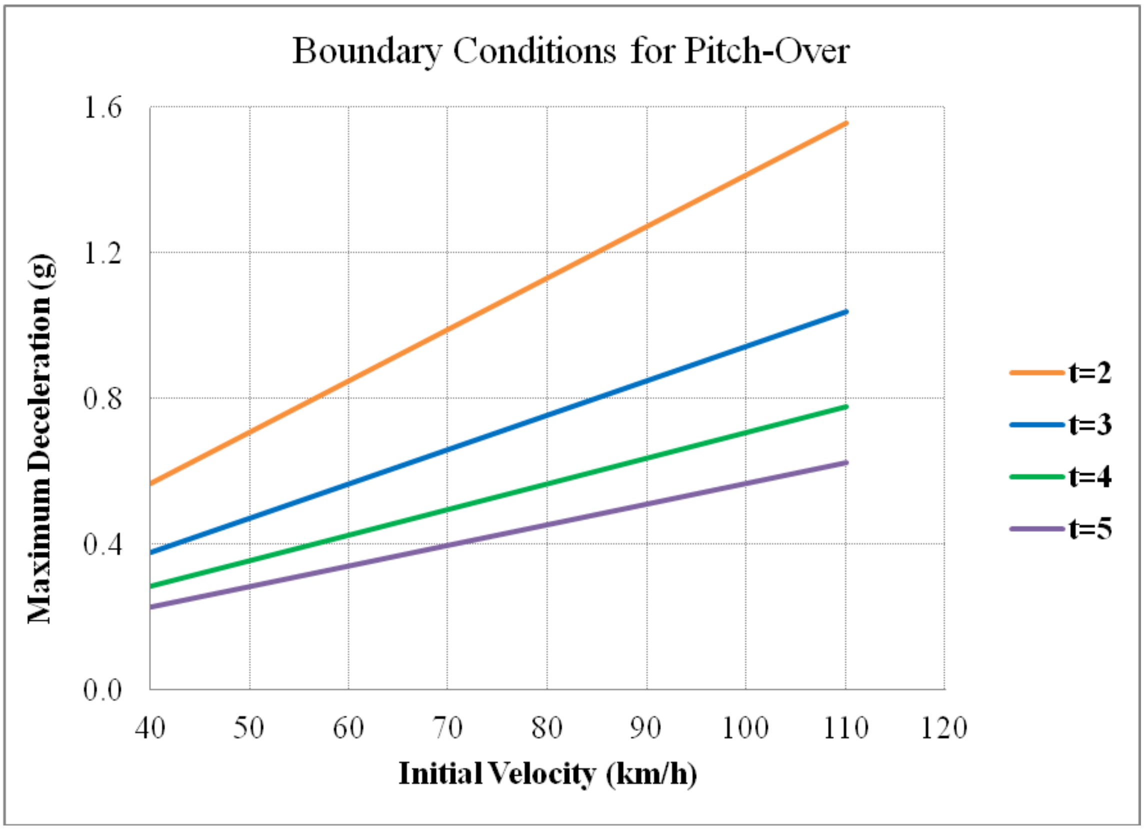

Figure 4. 13 Pitch-over boundary condition of deceleration ratio and initial velocity

Figure 4.13 shows the conditions for pitch-over boundaries for various maximum deceleration and initial velocities. ‘t’ is the time taken to bring the motorcycle from its initial velocity to rest. When braking duration is 1 second the deceleration rate is going above 1g and it leads to pitch-over. Similarly, when braking duration is 2 seconds, at lower speeds deceleration is below 1g whereas for higher speeds like 70 km/h and above, it exceeds 1g signalling condition for pitch-over. When motorcycle is brought to rest from 100 km/h using brake duration of 4 seconds and above, then the deceleration becomes below 1g and there is not pitch-over. When braking time is increased deceleration rate reduces proportionally and similarly when braking time is reduced the deceleration rate increases leading to pitch-over.

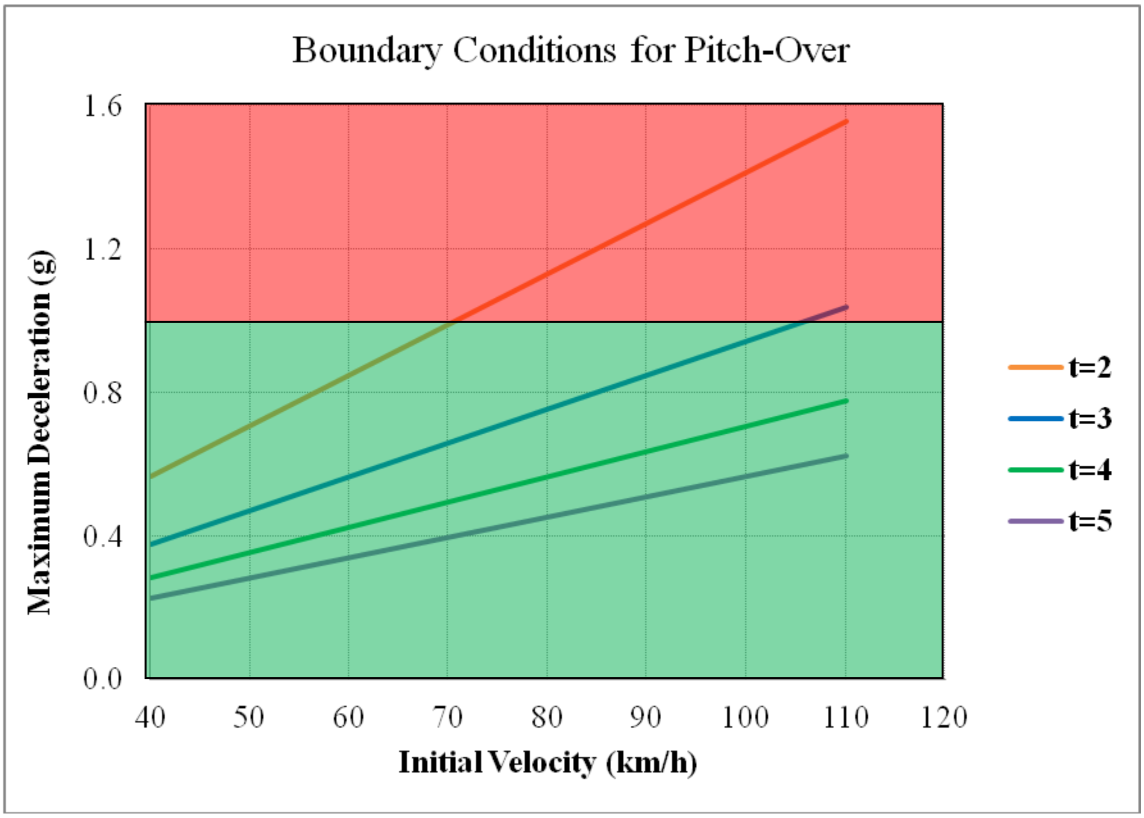

Figure 4. 14 Pitch-over boundary condition threshold zones

In figure 4.14 the area shaded green indicates the safe zone of operation where no pitch-over will occur and the red box zone is the pitch-over region.

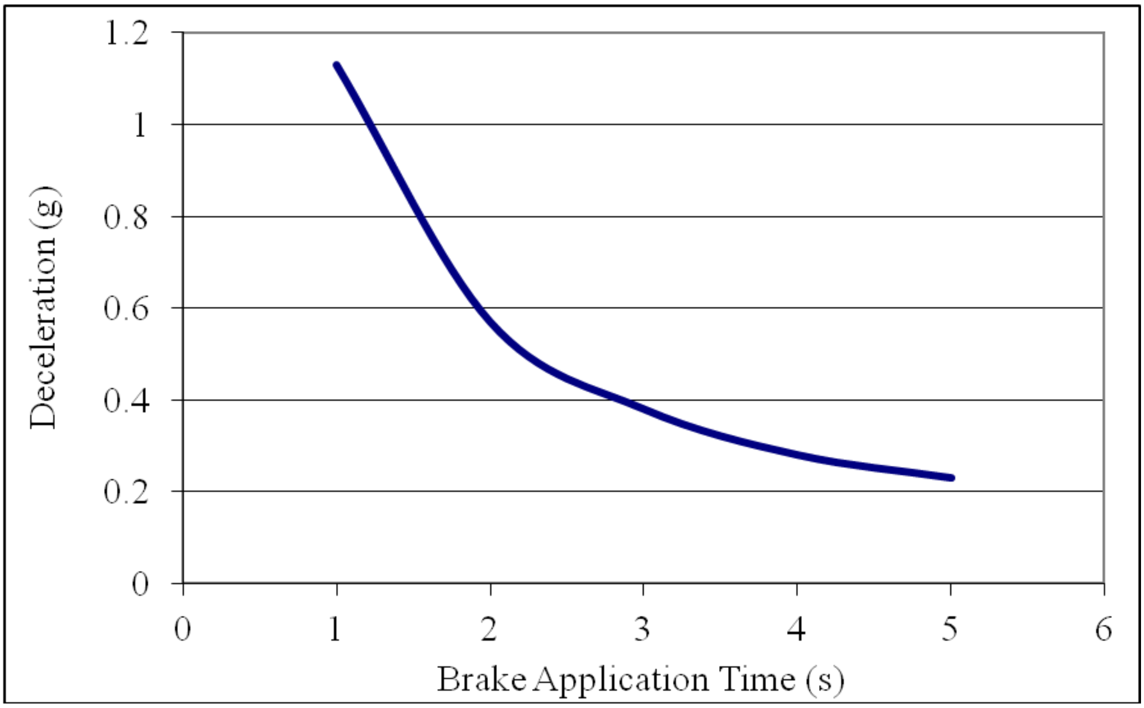

Figure 4. 15 Influence of brake duration on deceleration

In figure 4.15 influence of brake application duration on deceleration is presented. Shorter the brake duration higher is the deceleration. Hence, even in crowded street traffic, where speeds are low, if brake duration and stopping distance are short, there is a significant chance for pitch-over and the tendency increases rapidly with shortening time of application of brake. It is very important to keep brake duration within the safe range in order to control deceleration of the vehicle.

These are the outcome of this research work that can fill the identified gap,

- The safe operational envelope has been identified for given geometric and operational conditions.
- The methodology developed can be used for development of safe operational envelope for vehicles with different geometric and load parameters.
- The present study helps in identifying and designing features to the existing brake control systems to prevent pitch-over during panic braking.
- The present study provides an operational envelope identifying the thresholds for pitch-over that would inform the developments.

4.6 Conclusion

Conclusions and achievements of the work described in this thesis are discussed in this section. A review of significant points of major contributions is included. As has been shown in the previous sections, broad aims of the project, namely, development of an analytical model and development and validation of a numerical model based on commercial MBD software have been achieved. The MBD model built is able to simulate realistic pitch-over behaviour during braking and the comparison of results from test and simulation confirm that the model is valid. Finding the boundary condition for pitch-over using MBD model is a major contribution to study of pitch-over behaviour of motorcycle.

During braking the maximum deceleration achieved by the motorcycle is very important. The location of the centre of gravity of motorcycle and maximum deceleration ratio has the influence on pitch-over. By keeping the centre of gravity height of the motorcycle towards the ground as much as possible and keeping deceleration below 1g the motorcycle can be prevented from pitching-over during braking.

4.7 Guidelines for designing a control system

Based on the above conclusion a control system can be designed. This system, in order to control deceleration, should take care of brake force distribution between front and rear brakes and duration of brake application. By controlling the deceleration it is possible to ensure that at any point of time the vehicle deceleration ratio does not exceed 1. This system should communicate with brake system, ABS (if equipped) and ESP (if equipped). Motorcycle parameters, like wheel base, height of centre of gravity, distance from front/rear wheel contact point to the centre of gravity location of the motorcycle, depend on design and such parameters should be verified during design stage.

4.8 Recommendation for future work

More analytical work can be carried out to gather more information regarding the rider and various road conditions such as, road friction coefficient, inclination etc. Additional tests can be done in order to collect rider behaviour in detail. Also, more braking tests and acceleration tests can give some more data to validate the motorcycle model. Tests can be conducted on roads having various inclinations and friction coefficients.

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Appendix - A

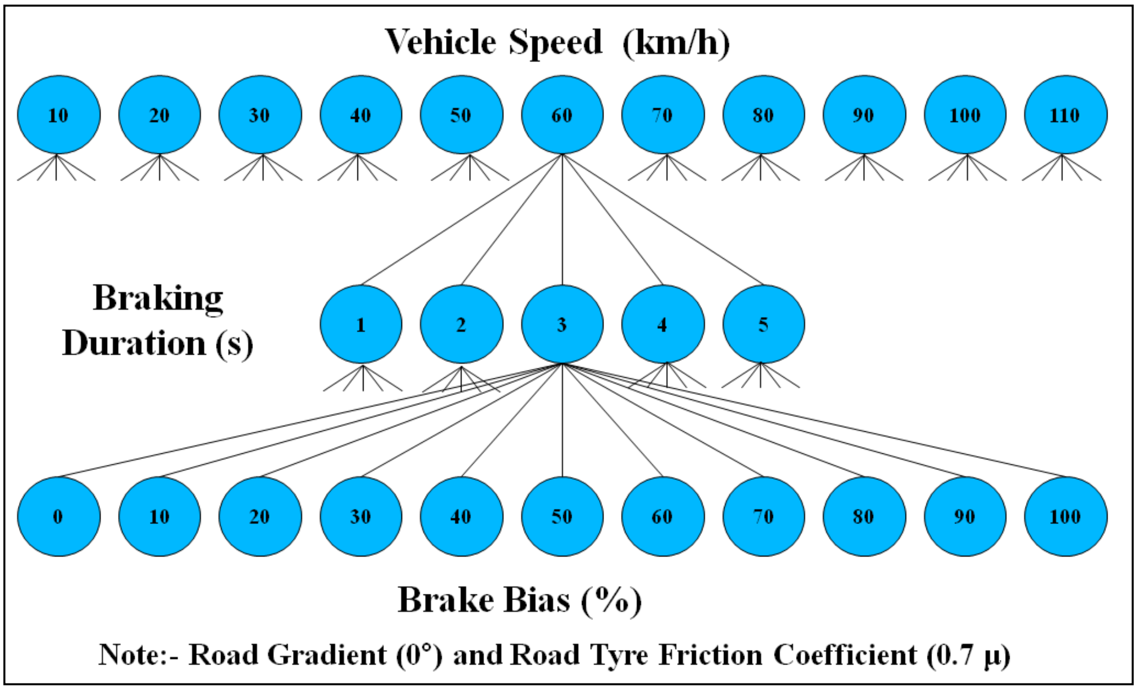

Figure A. 1 Simulation matrix

Table A. 1 Influence of various parameters on pitch-over

Initial Velocity (km/h)	Time (s)	Deceleration	Dynamic Load		ẍmax/g	(p-b)/h	$\frac{\ddot{x}_{max}}{g} \le \frac{p-b}{h}$
			Front	Rear			
110.0	1.0	30.6	4717.0	-2423.8	**3.11**	1.09	**-2.03**
100.0	1.0	27.8	4378.6	-2085.4	2.83	1.09	**-1.74**
90.0	1.0	25.0	4040.1	-1746.9	2.55	1.09	**-1.46**
80.0	1.0	22.2	3701.7	-1408.5	2.27	1.09	**-1.18**
70.0	1.0	19.4	3363.3	-1070.1	1.98	1.09	**-0.90**
60.0	1.0	16.7	3024.9	-731.7	1.70	1.09	**-0.61**
50.0	1.0	13.9	2686.5	-393.3	1.42	1.09	**-0.33**
40.0	1.0	11.1	2348.1	-54.9	1.13	1.09	**-0.05**
110.0	2.0	15.3	2855.7	-562.5	1.56	1.09	**-0.47**
100.0	2.0	13.9	2686.5	-393.3	1.42	1.09	**-0.33**
90.0	2.0	12.5	2517.3	-224.1	1.27	1.09	**-0.19**
80.0	2.0	11.1	2348.1	-54.9	1.13	1.09	**-0.05**
70.0	2.0	9.7	2178.9	114.3	0.99	1.09	**0.10**
60.0	2.0	8.3	2009.6	283.6	0.85	1.09	**0.24**
50.0	2.0	6.9	1840.4	452.8	0.71	1.09	**0.38**
40.0	2.0	5.6	1671.2	622.0	0.57	1.09	**0.52**
110.0	3.0	10.2	2235.3	57.9	1.04	1.09	**0.05**
100.0	3.0	9.3	2122.4	170.8	0.94	1.09	**0.14**
90.0	3.0	8.3	2009.6	283.6	0.85	1.09	**0.24**
80.0	3.0	7.4	1896.8	396.4	0.76	1.09	**0.33**
70.0	3.0	6.5	1784.0	509.2	0.66	1.09	**0.43**
60.0	3.0	5.6	1671.2	622.0	0.57	1.09	**0.52**
50.0	3.0	4.6	1558.4	734.8	0.47	1.09	**0.61**
40.0	3.0	3.7	1445.6	847.6	0.38	1.09	**0.71**
110.0	4.0	7.6	1925.0	368.2	0.78	1.09	**0.31**
100.0	4.0	6.9	1840.4	452.8	0.71	1.09	**0.38**
90.0	4.0	6.3	1755.8	537.4	0.64	1.09	**0.45**
80.0	4.0	5.6	1671.2	622.0	0.57	1.09	**0.52**
70.0	4.0	4.9	1586.6	706.6	0.50	1.09	**0.59**
60.0	4.0	4.2	1502.0	791.2	0.42	1.09	**0.66**
50.0	4.0	3.5	1417.4	875.8	0.35	1.09	**0.73**
40.0	4.0	2.8	1332.8	960.4	0.28	1.09	**0.80**
110.0	5.0	6.1	1738.9	554.3	0.62	1.09	**0.46**
100.0	5.0	5.6	1671.2	622.0	0.57	1.09	**0.52**
90.0	5.0	5.0	1603.5	689.7	0.51	1.09	**0.58**
80.0	5.0	4.4	1535.9	757.3	0.45	1.09	**0.63**
70.0	5.0	3.9	1468.2	825.0	0.40	1.09	**0.69**
60.0	5.0	3.3	1400.5	892.7	0.34	1.09	**0.75**
50.0	5.0	2.8	1332.8	960.4	0.28	1.09	**0.80**
40.0	5.0	2.2	1265.1	1028.1	0.23	1.09	**0.86**

In this table the safest braking duration of motorcycle for various speeds is presented and they were calculated using ADAMS simulations. Red colour indicated the scenario where pitch-over occurs and figures in green colour where pitch-over does not occur. In the table various parameters for a motorcycle running at different initial speeds and coming to rest in different brake duration are tabulated. It is evident that if the deceleration ratio $\ddot{x}_{max}/g$ is above one then the motorcycle will tend to pitch-over.

Appendix - B

Low Risk Research Ethics Approval

Annexure – 7 (for Sl. No. 11 of PHD01)

Low Risk Research Ethics Approval Checklist

Applicant Details

Name: Shijo Thomas	E-mail: thomasshijo@gmail.com
Department: Research	Date: 21-06-2012
Course: Ph.D.	Title of Project: Modelling and Control of Pitch-Over Phenomenon Due to Panic Braking in Motorcycles

Project Details

The aim of this work is to develop a control system for a motorcycle to reduce the occurrence of pitch-over event during panic braking. The system will specifically focus on maintaining stability even under rider response that is inappropriate for the panic situation.

Parametric studies and characterisation of pitch-over phenomena necessitates use of commercial numerical simulation tools. The simulation procedure adopted will be validating using selected motorcycle.

The documents required for the research will be collected from journals, conference proceedings and books from literature.

Participants in your research

1. Will the project involve human participants?		No

If you answered **Yes** to this questions, this may **not** be a low risk project.

- If you are a student, please discuss your project with your Supervisor.
- If you are a member of staff, please discuss your project with your Faculty Research Ethics Leader or use the Medium to High Risk Ethical Approval or NHS or Medical Approval Routes.

Risk to Participants

2. Will the project involve human patients/clients, health professionals, and/or patient (client) data and/or health professional data?		No
3. Will any invasive physical procedure, including collecting tissue or other samples, be used in the research?		No
4. Is there a risk of physical discomfort to those taking part?		No
5. Is there a risk of psychological or emotional distress to those taking part?		No
6. Is there a risk of challenging the deeply held beliefs of those taking part?		No
7. Is there a risk that previous, current or proposed criminal or illegal acts will be revealed by those taking part?		No
8. Will the project involve giving any form of professional, medical or legal advice, either directly or indirectly to those taking part?		No

If you answered **Yes** to **any** of these questions, this may **not** be a low risk project.

- If you are a student, please discuss your project with your Supervisor.
- If you are a member of staff, please discuss your project with your Faculty Research Ethics Leader or use the Medium to High Risk Ethical Approval or NHS or Medical Approval Routes.

Risk to Researcher

9. Will this project put you or others at risk of physical harm, injury or death?		No
10. Will project put you or others at risk of abduction, physical, mental or sexual abuse?		No
11. Will this project involve participating in acts that may cause psychological or emotional distress to you or to others?		No
12. Will this project involve observing acts which may cause psychological or emotional distress to you or to others?		No
13. Will this project involve reading about, listening to or viewing materials that may cause psychological or emotional distress to you or to others?		No
14. Will this project involve you disclosing personal data to the participants other than your name and the University as your contact and e-mail address?		No
15. Will this project involve you in unsupervised private discussion with people who are not already known to you?		No
16. Will this project potentially place you in the situation where you may receive unwelcome media attention?		No
17. Could the topic or results of this project be seen as illegal or attract the attention of the security services or other agencies?		No
18. Could the topic or results of this project be viewed as controversial by anyone?		No

If you answered **Yes** to **any** of these questions, this is **not** a low risk project. Please:

- If you are a student, discuss your project with your Supervisor.
- If you are a member of staff, discuss your project with your Faculty Research Ethics Leader or use the Medium to High Risk Ethical Approval route.

Informed Consent of the Participant

19. Are any of the participants under the age of 18?		No
20. Are any of the participants unable mentally or physically to give consent?		No
21. Do you intend to observe the activities of individuals or groups without their knowledge and/or informed consent from each participant (or from his or her parent or guardian)?		No

If you answered **Yes** to **any** of these questions, this may **not** be a low risk project. Please:

- If you are a student, discuss your project with your Supervisor.
- If you are a member of staff, discuss your project with your Faculty Research Ethics Leader or use the Medium to High Risk Ethical Approval route.

Participant Confidentiality and Data Protection

22. Will the project involve collecting data and information from human participants who will be identifiable in the final report?		No
23. Will information not already in the public domain about specific individuals or institutions be identifiable through data published or otherwise made available?		No
24. Do you intend to record, photograph or film individuals or groups without their knowledge or informed consent?		No
25. Do you intend to use the confidential information, knowledge or trade secrets gathered for any purpose other than this research project?		No

If you answered **Yes** to **any** of these questions, this may **not** be a low risk project:

- If you are a student, discuss your project with your Supervisor.
- If you are a member of staff, discuss your project with your Faculty Research Ethics Leader or use the Medium to High Risk Ethical Approval or NHS or Medical Approval routes.

Gatekeeper Risk

26. Will this project involve collecting data outside University buildings?		No
27. Do you intend to collect data in shopping centres or other public places?		No
28. Do you intend to gather data within nurseries, schools or colleges?		No
29. Do you intend to gather data within National Health Service premises?		No

If you answered **Yes** to **any** of these questions, this is **not** a low risk project. Please:

- If you are a student, discuss your project with your Supervisor.
- If you are a member of staff, discuss your project with your Faculty Research Ethics Leader or use the Medium to High Risk Ethical Approval or NHS or Medical Approval routes.

Other Ethical Issues

30. Is there any other risk or issue not covered above that may pose a risk to you or any of the participants?		No
31. Will any activity associated with this project put you or the participants at an ethical, moral or legal risk?		No

If you answered **Yes** to these questions, this may **not** be a low risk project. Please:

- If you are a student, discuss your project with your Supervisor.
- If you are a member of staff, discuss your project with your Faculty Research Ethics Leader.

Principal Investigator Certification

If you answered **No** to **all** of the above questions, then you have described a low risk project. Please complete the following declaration to certify your project and keep a copy for your record as you may be asked for this at any time.

Agreed restrictions to project to allow Principal Investigator Certification

Please identify any restrictions to the project, agreed with your Supervisor or Faculty Research Ethics Leader to allow you to sign the Principal Investigator Certification declaration.

Participant Information Leaflet attached. Informed Consent Forms attached.

Principal Investigator's Declaration

Please ensure that you:

- Tick all the boxes below and sign this checklist.
- Students must get their Supervisor to countersign this declaration.

I believe that this project **does not require research ethics approval**. I have completed the checklist and kept a copy for my own records. I realise I may be asked to provide a copy of this checklist at any time.	Y
I confirm that I have answered all relevant questions in this checklist honestly.	Y
I confirm that I will carry out the project in the ways described in this checklist. I will immediately suspend research and request a new ethical approval if the project subsequently changes the information I have given in this checklist.	Y

Signatures

If you submit this checklist and any attachments by e-mail, you should type your name in the signature space. An email attachment sent from your University inbox will be assumed to have been signed electronically.

Principal Investigator

Signed: Shijo Thomas .... (Principal Investigator or Student)

Date: 21-06-2012

Students storing this checklist electronically must append to it an email from your Supervisor confirming that they are prepared to make the declaration above and to countersign this checklist. This-email will be taken as an electronic countersignature.

Student's Supervisor

Countersigned...(Supervisor)

Date: 21-06-2012

I have read this checklist and confirm that it covers all the ethical issues raised by this project fully and frankly. I also confirm that these issues have been discussed with the student and will continue to be reviewed in the course of supervision.